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Short range propagation measurements at 2.4, 4.5 and 11.5 GHz in indoor and outdoor environments

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ABSTRACT (UNCLASSIFIED)

This report concerns the project "SHF Indoor/Outdoor Propagation Measurements", which has been carried out in cooperation with the Technical University of Delft.

Within this project a measurement system has been developed at FEL for wideband coherent propagation measurements (complex frequency response / channel impuls response). Measurements have been carried out at 2.4, 4.75 and 11.5 GHz in indoor (office and conference rooms) and outdoor (forest and open terrain) environments at distances within pico-cellular dimensions (< 50 m). For the outdoor measurements a special technique has been applied to extend the range to distances > 30 m.

In total over 1000 measurements have been performed under different conditions. In this report details on the measurement system that was used, and measurement results on path-loss, delay time spread τ_{RMS} and the influence of people on the channel (indoor situation), are presented.

The measurement results that are available now, form a good basis for further theoretical research and validation of this work, as well as for practical application research.

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SAMENVATTING (ONGERUBRICEERD)

Dit rapport betreft het project "SHF Indoor/Outdoor Propagation Measurements", dat in samenwerking met de Technische Universiteit Delft is uitgevoerd.

Binnen dit project is door het FEL een meetsysteem ontwikkeld voor het uitvoeren van breedband coherente metingen van de complexe frequentieresponsie en kanaalimpulsresponsie. Er zijn metingen uitgevoerd in "indoor" (kantoor- en conferentieruimten) en "outdoor" (bos en open terrein) omgevingen op 2.4, 4.75 en 11.5 GHz, op afstanden kleiner dan picocel afmetingen (< 50 m). Voor de "outdoor" metingen is een speciale techniek ontwikkeld om het meetsysteem voor afstanden > 30 m te kunnen gebruiken.

In totaal zijn er meer dan 1000 metingen onder verschillende omstandigheden uitgevoerd. In dit rapport worden het gebruikte meetsysteem en de resultaten m.b.t. paddemping, "RMS delay time spread" τ_{RMS} en de invloed van de aanwezigheid van mensen op het kanaal ("indoor" situatie), gepresenteerd.

De meetresultaten die nu beschikbaar zijn, vormen een goede basis voor zowel verder theoretisch onderzoek en validatie van dit onderzoek als voor praktisch toegepast onderzoek.

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1 INTRODUCTION

1.1 Wireless communications

The demand for (personal) wireless communications, voice as well as data, is increasing very fast. This trend is expected to continue in the future, especially in dense business environments. Different types of communiactions systems, anticipating to this demand, are already available:
- mobile communications: high power, voice and data, long range access,
- cordless telephones and paging: low power, mainly voice applications, medium range access,
- cordless local area networks (CLAN): low power, high datarate, especially for in-door and short range out-door applications.

Integration of mobile radio, cordless telephone, paging and wireless LAN's may eventually lead to a universal portable telephone or terminal for both speech and data communication, based on micro- (distance < 2 km) and pico-cellular (distance < 50 m) structures with cells as small as a building or even a single room.

CLANs don't use a wire link, but another type of medium. Three types of CLANs can be distinguished:
- those which use the electromagnetic (e.m.) radio spectrum (at this moment systems are offered which operate up to 18 GHz),
- those which use Infra-Red light, also part of the e.m. spectrum,
- those which use ultra sound (above 20 kHz), which operate at low datarates, but are especially suited for harsh environments.

In the following we will deal only with the category of CLANs operating in the e.m. radio spectrum, which are based on a picocellular structure.

Computer networking, as we know it, has always required cable as network medium. However, radio networks have a number of inherent advantages over wire networks. These advantages are:
1. Elimination of wiring around buildings totally or for a significant part.
2. Before installation no lengthy planning procedures are required.

3. Relocation of terminals and adaptation of the network is easy, fast and cheap. This will contribute to efficiency improvement because less time is spilled due to employees unable to have access to the network when they need to.
4. The flexibility of providing services for a large number of users.

CLANs use a radio link as network medium. The radio link can be shared by different terminals or by a terminal and a base station. The advantages of CLANs are the increased mobility of the terminals. It makes fast and reliable connectivity possible without the use of wires. Changes and moves of terminals are easily implemented and cost very little time and almost no additional organisation.
In the higher frequency bands (> 1GHz) large bandwidths are available so that high bitrates can be supported easily, at this moment already up to 10's of Mbit/s.
CLANS, however, will not make cabled computer networks completely redundant. Three basic options for application of CLANs can be identified.

1. CLANs can integrate successfully into existing cabled computer systems. In this case the overall network medium will use a mix of different transmission media (hybrid medium). Between terminals and a base station a radio link is used as medium, and between the base stations and servers a cable (copper or optical fibre) can be used as backbone network. The only limitation is that a base station should be available within reasonable distance.
2. CLANs can offer reliable full wireless, stand-alone capability, connecting a number of terminals, one of which acts as server.
3. CLANs are well suited for open areas where it is impractical or impossible to run cabling.

At this moment still a number of drawbacks of radio links exist, which prevent from massive use and implementation. The most important obstacles are:

- No regulations are available for the use of the e.m. spectrum for CLANs, however this will change within short time.
- Interference problems of different sytems which operate within short distances in the same frequency band will occur. This puts high requirements on interference immunity and power control requirements.
- Security requirements, standards and regulations.
- No widespread knowledge is available at the moment. Many applications are still in development.

1.2 Frequency bands assigned for wireless LAN communication

The frequency bands that are in use at this moment in the United States for CLANs are 900 MHz, 1.8 and 2.4 GHz. Systems that will become available in the near future will operate in frequency bands up to 60 GHz.
At this moment there is no pan-European frequency allocation for CLANs. However, the frequency management group of the CEPT (Conference of European Postal and Telecommunication administration) has agreed to open five frequency bands for CLANs: 2.4, 5.7 - 5.8, 17.1 - 17.3, 24.1 and 61 GHz. This decision still has to be endorsed, [1].

The use of the higher frequency bands have a number of special advantages for application in CLANS, when compared to the lower bands which are used in Cordless Telephone (1.8 GHz) and mobile radio networks (900 MHz).

1. The high propagation loss combined with intelligent power control offers a low interference environment even with a large number of users, when related to the distance. This makes frequency re-use within a small cellular structure possible. This is especially suitable for in-door environments.
2. Higher data rates can be supported.
   This makes that even in dense user environments the high demand for communication capacity can be fulfilled.

1.3 Existing wireless LAN systems

Some manufacturers already offer commercial CLAN systems.

- NCR

NCR's WaveLAN operates in the 900 MHz band (902 - 928 MHz), [2]. The network cabling is replaced with high-frequency radio signals. Direct Sequence Spread Spectrum (DS-SS) modulation is used in combination with CSMA (Carrier Sense Multiple Access) to reduce interference.
The transmission speed can be up to 2 Mbit/s over unobstructed distances of 250 m. The system for a terminal consists of a single plug-in card with a small antenna. The price at this moment is $ 1400,-.

- Telesystems SLW

Telesystems SLW offers a low-cost DS-SS packet switched CLAN, which operates in the 900 MHz and 2.4 GHz band.

- Motorola

Motorola offers the Altair wireless Ethernet CLAN system which operates at 18 GHz, [3]. It offers a 15 Mbit/s signalling rate which is compatible with the 10 Mbit/s Ethernet rate. In every microcell a Control Module is placed which is able to service 32 User Modules. The coverage area of a microcell is about 500 m^2. The Motorola system offers two different security features:

- data scrambling,
- restricted access only to registered users.

- Apple

Apple is planning to come with a CLAN system.

1.4 Signal transmission in indoor and outdoor environments

In general two main restrictions can be identified which limit the performance of signal transmission systems.

1. Physical restrictions:

The most important physical restrictions are signal propagation effects (attenuation, dispersion and distortion) and thermal noise.
In the past many successful research efforts have been made to counter these negative aspects of radio transmission by means of optimum modulation techniques, antenna design, frequency choice and low-noise amplifier design, etc.

2. Cultural restrictions:

At this moment cultural restrictions are becoming more and more problematic and often limiting. These restrictions are due to the dense use of the frequency spectrum: interference, man made noise, signal collisions etc.
Different solutions are applied to counter these effects, like using higher frequency bands, coding techniques, special modulation techniques (spread spectrum modulation), power management and transmission protocols.

A comprehensive knowledge about signal propagation characteristics over different types of environments and, more specifically, in buildings, is one of the key factors in designing future short range indoor and outdoor cellular mobile radio systems.

In short range indoor and outdoor wireless communications, special propagation problems arise due to the highly reflective and shadowing environment, which are more or less related to the problems also present in outdoor mobile communications. The environments, which depend strongly on the type of buildings (material, dimensions etc.), will cause that propagation from radio signals will take place via multiple paths which differ in amplitude, phase and delay time. This means that the received signal suffers from time dispersion due to the differeneces in propagation times. This time dispersion limits the maximum channel symbol rate significantly when no special precautions are taken, like frequency- or antenna diversity, or adaptive equalization.

1.5 Overview of recent literature

In recent years a lot of results on indoor communications aspects have been published, especially on propagation studies, modulation- and diversity techniques. Measurements results have been reported for different types of environments and at different frequencies up to 5.8 GHz.
In [4] a comprehensive overview is given of the research results for indoor mobile communications as published in the recent literature. This work has been carried out as a Task-project at the Technical University Delft.
In [5] an overview is given of propagation measurement results in different types of environments, into and within buildings. In this article a division in different environment types with comparable characteristics, is suggested like houses, offices, factories, airports and undergrounds.

1.6 Overview of the contents of this report

In this report the measurement systems, which have been used at FEL-TNO for indoor and outdoor measurements, and the measurement results obtained, will be described. The measurements have been performed in three frequency bands: 2.4, 4.75 and 11.5 GHz, to characterize the indoor and outdoor propagation channels.

In chapter 2 the multipath propagation channel is modeled and different parameters to characterize the channel are identified. In chapter 3 different measurement principles are discussed.

Chapter 4 contains the description of the measurement system and scenario for indoor measurements and in chapter 5 the results of these measurements are presented.

In chapter 6 the measurement system and scenario for outdoor measurements are given. In chapter 7 the results of these mesurements are discussed.

Finally conclusions and recommendations for further work are given.

2 CHANNEL MODEL AND DEFINITION OF RELEVANT PARAMETERS FOR SYSTEM DESIGN

In this chapter a model for short range indoor/outdoor multipath channels, which is generaly used in research publications in this field, will be discussed. Based on this model a number of relevant parameters, that are important in communications system designs and the assessment of system performance, wi' be indicated and described.

2.1 The channel model

In general the short range indoor/outdoor multipath channel is represented by multiple paths each having a real positive gain β_k, propagation delay τ_k and phase shift θ_k, where k is the path index. The baseband complex response of the k^{th} path is given by:

$$h_k(t) = \beta_k \exp\{j\theta_k\}\delta(t-\tau_k) \tag{2.1a}$$

Now the baseband complex channel impulse response is modeled as, [6]:

$$h(t,x) = \sum_{k=1}^{N} \beta_k \exp\{j\theta_k\}\delta(t-\tau_k), \tag{2.1b}$$

where $\delta(.)$ is the Dirac delta function. h(t,x) is the time domain response which is also position dependent (indicated by x). N is the number of paths (k=1 indicates the first arriving path).
Because of the motion of people, or other time varying environmental factors, the parameters β_k, τ_k and θ_k are randomly changing functions of time. However the rate of their variations is assumed to be very slow compared to any useful signaling rates that are likely to be considered. Therefore, these parameters are treated here as virtually time-invariant random variables when compared to the data rate.

Another way to represent the response of the multipath channels is in the frequency domain by $H(f,x) = \mathcal{F}\{h(t,x)\}$, which is the Fourier Transform of the impulse response h(t,x).
When the parameters β_k, τ_k and θ_k are known from measurements, the multipath channel characteristics can be calculated.

2.2 Narrowband and wideband channels

In a multipath channel the maximum datarate which is usable, is limited by time dispersion. The radio channel can be classified in two types of channels, depending on the application. When the transmission bandwidth is narrow compared to the coherence bandwidth of the channel, the channel is called a narrowband channel. When the transmission bandwidth is in the order of or larger than the coherence bandwidth, the channel is called a wideband channel.
The coherence bandwidth is the bandwidth over which the signal propagation characteristics are correlated. For a signal bandwidth which is much less than the coherence bandwidth, fading will be constant for the total signal bandwidth, so called flat- or non-frequency selective fading, and therefore, will not cause signal distortion. The channel response can be assumed flat over small bandwidths.
For wideband signals however, the fading will be frequency dependent over the signal spectrum, and will in general distort the signal seriously.
To determine the characteristics of narrowband and wideband channels different measurement techniques are used.

2.2.1 Narrowband channel

For narrowband channels a narrowband signal, like an unmodulated carrier, can be used to determine the relevant parameters. The propagation loss or received signal power is measured as function of position at a single frequency. From these measurements the power and fading statistics can be calculated.

2.2.2 Wideband channel

To determine the characteristics of wideband channels, a wideband signal has to be used, eg. a narrow puls, or another type of wideband signal. From the measurement results propagation loss and delay time statistics can be calculated.
In the following we will only deal with wideband channels.

When the broadband characteristics of a multipath channel are measured, a wideband, often pulselike sense signal is used. The transmitted sounding signal can be written as:

$$s(t) = p(t)\exp\{j(\omega_c t+\phi)\}, \tag{2.2}$$

where p(t) is the pulse signal, and ω_c is the carrier frequency. The received signal is now:

$$r(t) = s(t) * h(t) = \sum_{k=1}^{N} \beta_k p(t-\tau_k) \exp\{j(\omega_c(t-\tau_k)+\phi+\theta_k)\} \tag{2.3}$$

The pulsewidth of p(t), or equivalently the measurement bandwidth, determines the achievable resolution in the time domain.

2.3 Channel parameters relevant for wideband communications system design

In this paragraph an overview will be given of the relevant parameters which can be derived from the channel impulse response h(t) or its Fourier transform H(f). In the following the position indicator x will be omitted.

- Power Delay Profile

The power delay profile (PDP) gives the distribution of the received signal power in time.
The PDP is defined as:

$$P(t) = h(t)h^*(t) = |h(t)|^2 = \sum_{k=1}^{N} \beta_k^2 \delta(t-\tau_k) \tag{2.4}$$

where * denotes the complex conjugate.
In an actual situation the transmitted pulses have a finite width. Then the PDP is calculated with (2.2):

$$P'(t) = |r(t)|^2 = \sum_{k=1}^{N} \sum_{l=1}^{N} \beta_k \beta_l p(t-\tau_k) p(t-\tau_l) \cdot \exp\{j(\omega_c(\tau_l-\tau_k)+\theta_k-\theta_l)\} \tag{2.5}$$

When we make the reasonable assumption that all θ_k's are statistically independent and uniformly distributed over $[0, 2\pi)$, then the mathematical expectation with respect to θ leads to the following simplification:

$$E_\theta\{|r(t)|^2\} = \sum_{k=1}^{N} \beta_k^2 p^2(t-\tau_k) \tag{2.6}$$

This averaging can be accomplished by averaging channel impulse responses measured at different frequencies or different positions within a small area (a few λ^2), where the β_k's and τ_k's can be assumed constant.

In figure 2.1 the PDP and the corresponding frequency response is given for an indoor channel at 4.75 GHz.

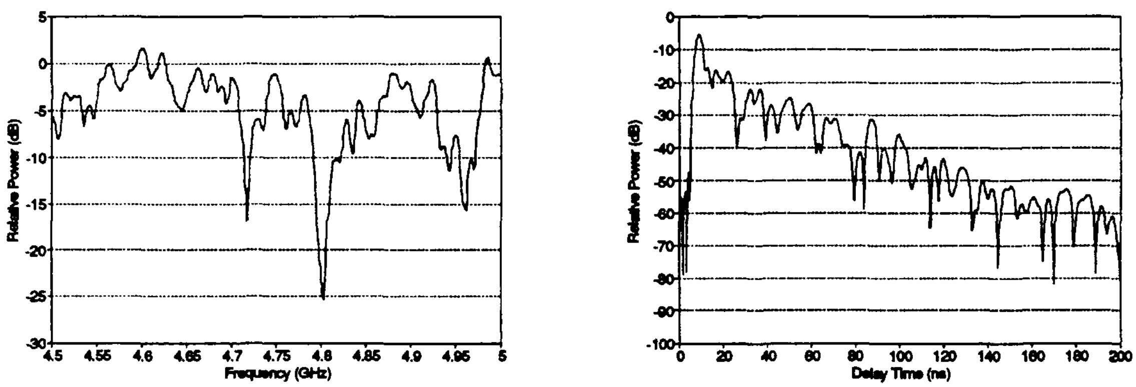


Fig. 2.1: Frequency response and Power Delay Profile of an indoor channel at 4.75 GHz.

- RMS Delay Time Spread

The Root Mean Square (RMS) Delay Time Spread (or RMS delay spread) is a very important parameter of the multipath radio channel. It is a measure for the spreading of the received signal power over time, and therefore, of the amount of signal dispersion. The RMS delay time τ_{RMS} is defines as:

$$\tau_{RMS} = [\int_{-\infty}^{\infty} (t-\tau_m)^2 P_{norm}(t)dt]^{1/2} \qquad (2.7)$$

τ_m is the mean excess delay time. This means the mean delay time of the total received power after the reception of the first path. The mean excess delay time is defined as:

$$\tau_m = \int_{-\infty}^{\infty} t P_{norm}(t)dt \qquad (2.8)$$

$P_{norm}(t)$ is the normalized PDP: $P_{norm}(t) = P(t)/P_{tot}$, with P_{tot} is:

$$P_{tot} = \int_{-\infty}^{\infty} P(t)dt \tag{2.9}$$

The delay spread τ_{RMS} is useful in assessing the performance and limitations of different modulation types and diversity principles. With τ_{RMS} a rough indication can be determined for the maximum datarate which can be supported by the channel, without making use of special equalizing or diversity techniques. The estimate of the maximum datarate is given by, [7]:

$$R_{max} = \frac{1}{4\tau_{RMS}} \tag{2.10}$$

When equalizing- or diversity techniques are applied, higher data rates than given by (2.10) are possible.

- Coherence bandwidth

The coherence bandwidth is the bandwidth over which the signal propagation characteristics are correlated. When wideband coherent measurement results are available, the coherence bandwidth B_c is defined as the -3 dB width of the amplitude of the complex autocorrelation function, $|R(\Delta f)|$, of the frequency response H(f). $R(\Delta f)$ [dB] is defined as follows:

$$R(\Delta f) = 10\text{Log}\{\int_{-\infty}^{\infty} H(f)H^*(f+\Delta f)df\} \tag{2.11}$$

The coherence bandwidth B_c and the delay spread τ_{RMS} are related as:

$$B_c = \frac{1}{\alpha\tau_{RMS}} \tag{2.12}$$

Theoretically the value of α is 2π when the PDP has an exponential distribution, [14]. However in a practical situation the value of α is not constant, it dependends on the PDP. From results in the literature [7, 8, 9] it follows that the value of α is between 5 - 7.

- Mean Signal Power and Signal Power variance

From the wideband frequency response H(f), it is possible to determine the signal power statistics over the measured frequency range. In figure 2.1 the power spectrum is shown for an LOS indoor situation at 4.75 GHz.

During a measurement the received power level is determined at 801 equidistant frequency points. The power level of the i^{th} frequency point $G_i = H(f_i)H^*(f_i)$. Note that these separate measurements G_i are narrowband measurements. Now the mean value and the variance of G(f) over the covered frequency range, can be calculated with:

$$E_f[G] = \frac{1}{L} \sum_{i=1}^{L} G_i \tag{2.13}$$

L is the number of frequency points. For the measurements performed here, L = 801. G_i is the measured power level at frequency point i.

The mean power level can also be determined from the path gains β_k. When we assume that the path configuration (number of paths, delay-times and path gains) is stable, small changes in position cause different summations of the path amplitudes because of the phase differences. The mean gain at a certain frequency is now determined by averaging the total signal over all possible phase combinations. This results in (see also (2.6)):

$$E_\theta[G] = \sum_{k=1}^{N} \beta_k^2 \tag{2.14}$$

In theory $E_f[G]$ and $E_\theta[G]$ are equal. In the following E[G] will be used.

The sample variance of G is defined by:

$$G_{RMS} = [\frac{1}{N-1} \sum_{i=1}^{N} (G_i - E[G])^2]^{1/2} \tag{2.15}$$

- Path loss as function of distance

Different models have been postulated to calculate path loss as funtion of distance in an indoor environment. Often the following simple model is used to describe the path loss, [10, 11]:

$$Loss = S(d_0) + 10.a.Log(d/d_0) \tag{2.16}$$

Here a is the mean power loss exponent of the environment and d [m] is the distance between the transmit and receive antennas. $S(d_0)$ is the free space loss over a path of d_0 meter. In general d_0 = 1m is chosen. When this parameter is measured with the antennas in far field conditions, also the antenna gains are taken into acount.

In the figures 2.2, 2.3, and 2.4 the propagation loss at the frequency bands 2.4, 4.75 and 11.5 GHz is given as function of the distance with parameter a.

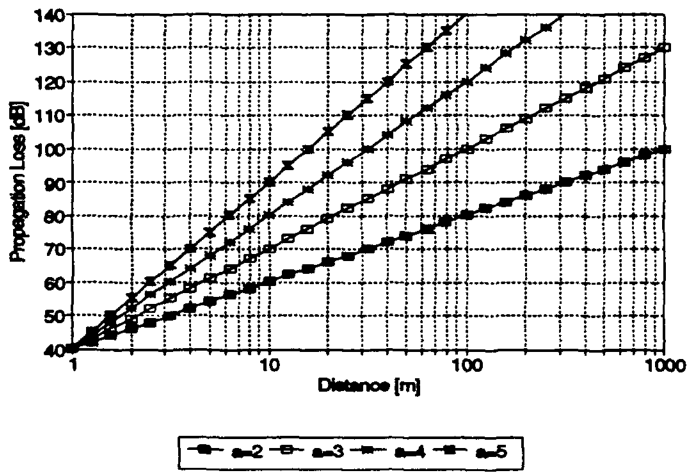


Fig. 2.2: Propagation loss at 2.4 GHz.

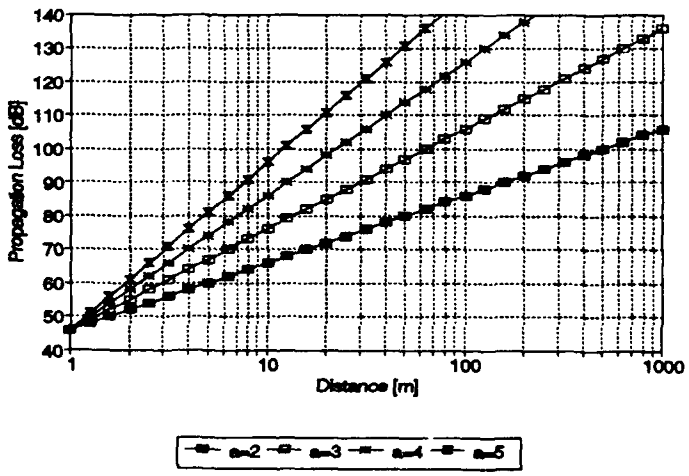


Fig. 2.3: Propagation loss at 4.75 GHz.

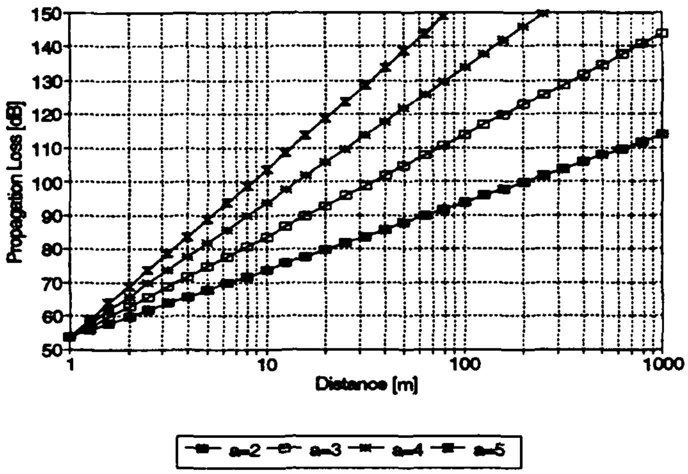


Fig. 2.4: Propagation loss at 11.5 GHz.

The propagation loss at one meter is taken to be the free space loss at this distance given by:

$$S(f,d) = 20\log\frac{4\pi d}{\lambda}$$

$$= -27.5 + 20\log(d) + 20\log(f)$$

$$S(f,d_0) = -27.5 + 20\log(f) \qquad (2.17)$$

with f in MHz.

When the antenna gain is taken into account (Appendix A), this results in:

$S(d_0) = 41.7$ dB at 2.4 GHz

$S(d_0) = 47.8$ dB at 4.75 GHz

$S(d_0) = 55.8$ dB at 11.5 GHz

The measured values of $S(d_0)$ were:

$S(d_0) = 43.1$ dB at 2.4 GHz

$S(d_0) = 48.4$ dB at 4.75 GHz

$S(d_0) = 57.6$ dB at 11.5 GHz

These values show a slight increase w.r.t. the theoretical values.

When it is tried to fit the results of practical measurements from indoor situations with this model, the deviations are very large. Especially the value for n may change significantly (from less than 2 in a hall-way situation, to more than 6 when the signal crosses walls and floors). This is because the indoor environment is entirely different from the outdoor mobile channel. In indoor situations different building materials are present (stone, enforced concrete, metal, wood, (coated) glass, etc.) each having their own reflection and transmission coefficients. Over short distances multiple crossings of walls and/or floors may occur. Furthermore the objects are in general much larger than the wavelength which means that diffraction effects are limited and shadowing will play a more important role.
Based on indoor measurements it was found that wall and floor crossings cause significant stepwize attenuation. When this is taken into account in formula (2.16) a much better fit is achieved.
The following two models are derived from the measurementfrom measurement results at 914 MHz in [10, 11].

- Model 1

Model 1 describes the propagation loss in the case that one or more floors are crossed:

$$\text{Loss} = S(d_0) + 10.a.\text{Log}(d/d_0) + \text{FAF} \tag{2.18}$$

where a is the mean power loss exponent of the particular floor (often in the order of 3) and FAF is the Floor Attenuation Factor, which is dependend on the number of floors and the construction materials used. In general FAF is not a linear function of the number of floors between transmitter and receiver.

- Model 2

Model 2 is a model to predict the attenuation loss at the same floor with wall crossings. The model is given by:

$$\text{Loss} = S(d_0) + 20.\text{Log}(d/d_0) + \sum_{i=1}^{k} m_i.\text{WAF}_i \tag{2.19}$$

In this model it is assumed that the propagation loss consists of the free-space loss term with added specific losses for wall crossings. m_i is the number of walls of a certain type of material and WAF_i is the Wall Attenuation Factor for that specific type of wall.
For accurate prediction results, the loss which is caused by different types of walls and floors has to be measured at different frequencies.

3 MEASUREMENT TECHNIQUES

In the previous chapter the channel parameters of interest for system design, have been discussed. We concluded already that wideband measurements are necessary to investigate radio channels for the applications of interest. The following channel signal characteristics need to be measured for determination of specific important channel parameters.

- RMS delay spread and mean delay

These parameters can be calculated from the power delay profile. This profile is determined by pulse measurements or calculated from wideband coherent sweep measurement results.

- Coherence bandwidth

The coherence bandwidth is calculated from the power measurements over a certain frequency band. These measurements should be performed coherently.

- Mean signal power and signal power variance

These parameters are calculated from the power measurements over a certain bandwidth. The measurements can be performed coherently as well as non-coherently.

- Path-loss as function of distance

This parameter is calculated from the mean signal powers determined over a certain bandwidth, from measurements performed at different positions at different distances.
It is also possible to use local mean value results of narrow band measurements. The local mean power value is the mean power averaged ove.: a small area or distance (often a 40λ track is used).

3.1 Measurement principles

For the performance of wideband channel measurements different channel sounding principles can be used. In the following the principles that are used mostly, will be discribed, [12].

- Pulse sounding

When a pseudo-impulse (a short duration pulse) is used to exite the propagation channel, the received signal represents the convolution of the sounding pulse with the channel impulse response. To observe the time varying behaviour of the channel, periodic pulse sounding should

be employed. The pulse repetition frequency has to be sufficiently rapid to allow observation of the time-varying response of individual propagation paths, but also low enough to ensure that all multipath echoes have decayed between successive impulses. The duration of the pulses determine the minimum echo resolution, i.e the minimum descernible path difference between echo contributions. The repetition rate determines the maximum unambiguous echo delay-time, i.e. the maximum distance for which an echo contribution can be unambiguously resolved.
In general pulse sounding systems use an envelope detection technique, and therefore the phase information of the different paths is lost.
The major limitation of the periodic pulse sounding technique is its requirement for a high peak-to-mean power ratio to provide adequate detection of weak echoes. A possible way to overcome this limitation of pulse transmitters, is to use a sounding method which provides pulse compression.

- Pulse compression techniques

The basis for all pulse compression techniques is contained in the theory of linear systems. It is well known that if white noise n(t) is applied to the input of a linear system, and if the output w(t) is crosscorrelated with a time-delayed replica of the input n(t-τ), then the resulting crosscorelation coefficient is proportional to the impulse response of the system h(t) evaluated at the delay time τ. This can be shown as follows:

$$E[n(t)n^*(t-\tau)] = R_n(\tau) = N_o\delta(\tau) \tag{3.1}$$

$R_n(\tau)$ is the autocorrelation function of the white noise, and N_o is the single sided noise power spectral density. When the system output is given by the convolution relationship:

$$w(t) = \int h(\zeta)n(t-\zeta)d\zeta, \tag{3.2}$$

the crosscorrelation of the output and the delayed input is given by:

$$\begin{aligned} E[w(t)n^*(t-\tau)] &= E[\int h(\zeta)n(t-\zeta)n^*(t-\tau)d\zeta] \\ &= \int h(\zeta)R_n(\tau-\zeta)d\zeta = N_o h(\tau) \end{aligned} \tag{3.3}$$

So the impulse response of a linear system can be evaluated using white noise and some method of correlation processing.

In practice however, it is unrealistic to use a white noise signal. Experimental systems must deploy deterministic waveforms with a noiselike character. The most widely known examples of such waveforms are pseudo-random binary (PN) sequences (i.e. Maximum Length sequences). These noiselike sequences are very popular, since they are easily generated using linear feedback shift registers, and posses excellent periodic autocorrelation properties ([13]), as illustrated in figure 3.1.

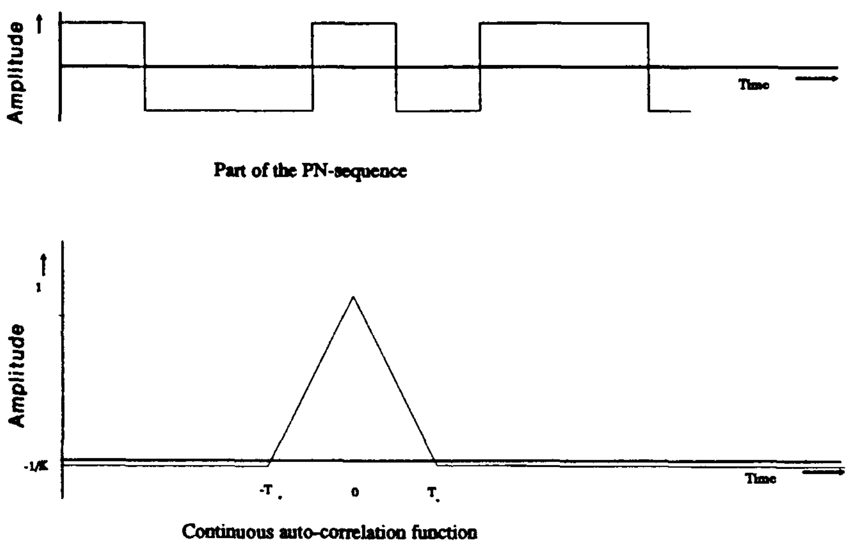


Fig. 3.1: Autocorrelation function of a PN-sequence.

The autocorrelation function of a PN-sequence is a triangular shaped function given by:

$$R_{PN}(\tau) = \begin{cases} 1-(K+1)|\tau|/KT_c & \text{for } |\tau| < T_c \\ -1/K & \text{for } |\tau| > T_c \end{cases} \qquad (3.4)$$

T_c is the chip duration, the width of the correlation pulse is $2T_c$. K is the length of the sequence (in chips) and also the periodicity of the correlation function.

The correlation of the received signal can be done by hardware correlators (like Surface Acoustic Wave correlators), or by software signal processing. This last methods can results in a much better resolution but is also very processing power consuming, [13].

3.2 Coherent frequency response measurements

The equipment available today, like coherent wideband network analysers up to 100 GHz, makes it possible to carry out an almost instantaneous measurement of the impulse response of the radio channel, [16]. The technique deploys complex frequency response measurements of the channel with a coherent signal, and Fourier transformation to achieve the impulse response. This technique is used for the measurements described in the remainder of this report and will be disussed in further detail in the following.

3.2.1 Details of the coherent frequency response measurement technique

As we have seen, a wideband coherent measurement technique is needed to characterize the wideband channel by its impulse response as given in (2.1b). Coherent because the phase releations are important too.

In the coherent frequency response measurement technique used here, the fact is used that the channel impulse response is the inverse Fourier transform of the frequency response. During the measurement the radio channel is sampled in the frequency domain. This means that amplitude and phase of the channel response is determined (coherently) at a number of N equidistant frequencies, which actually results in a sampled version of the frequency response. The impulse response is calculated by taking the inverse Fourier transform of this sampled frequency response.

3.2.2 Important measurement parameters

The following measurement parameters are important for the final result:

- the total bandwidth over which the samples are taken: BW_m,
- the number of points N,
- the type of window that is used before taking the inverse Fourier transform.

3.2.2.1 Resolution verses bandwidth

The bandwidth over which the samples are taken determines the time resolution that is achieved for the calculated impulse response after inverse Fourier transformation. When the measurement bandwidth is indicated as $BW_m = f_{max} - f_{min}$, the resolution is given by the following relation:

$$\tau_{res} = \frac{1}{BW_m} \tag{3.5}$$

For a BW_m = 1 GHz, the resolution is 1 ns.

3.2.2.2 Unambiguous range versus frequency distance between sample points

The unambiguous range of the measurement is the distance [meters] or the duration [seconds] over which the received energy of the impulse response can be unambiguously related to a certain distance. For larger distances the aliasing effect, which is due to undersampling in the frequency domain, causes erroneous results. The frequency distance between the sample points or the number of point over BW_m, determines the unambiguous range that is available. This range is given by:

$$R_{unamb} = \frac{c}{\Delta f_{samp}} \text{ [m]} \tag{3.6}$$

where Δf_{samp} is the sample distance in the frequency domain and c is the speed of light. Or

$$\tau_{unamb} = \frac{1}{\Delta f_{samp}} \text{ [s]} \tag{3.7}$$

In the following it is assumed that the samples are taken equidistant over the measurement bandwidth BW_m. For Δf_{samp} = 1 MHz, τ_{unamb} = 1 μs and R_{unamb} = 300 m.

3.2.2.3 The influence of windowing

Before inverse Fourier transformation the samples should be weighted or windowed, in order to suppress undesired sidelobes.

When direct transformation is applied, which is equivalent with a rectangular window, the output function is the resultant of the convolution of the desired response and a sinc function in the time domain belonging to the rectangular frequency window. This results in the occurrance of sidelobes in the time domain, [2]. Suppression of these sidelobes can be achieved by applying a suitable wondow function.

The effect of windowing is broadening of the pulse in the time domain by a factor in the order of 1.5 - 2. Therefore, the window has to be chosen carafully so that an optimum is found between pulse width and sidelobe strength. For the measurements the Hanning window was used, which gives a pulse width broadening of about 1.5. Other much used window functions are the Kaizer and Blackman-Harris windows.

4 INDOOR MEASUREMENTS IN OFFICE ENVIRONMENT

4.1 Measurement setup

In figure 4.1 the general set-up of the measurement system is given. With this set-up channel measurements have been performed in an indoor environment at three frequency bands: 2.4, 4.75 and 11.5 GHz.

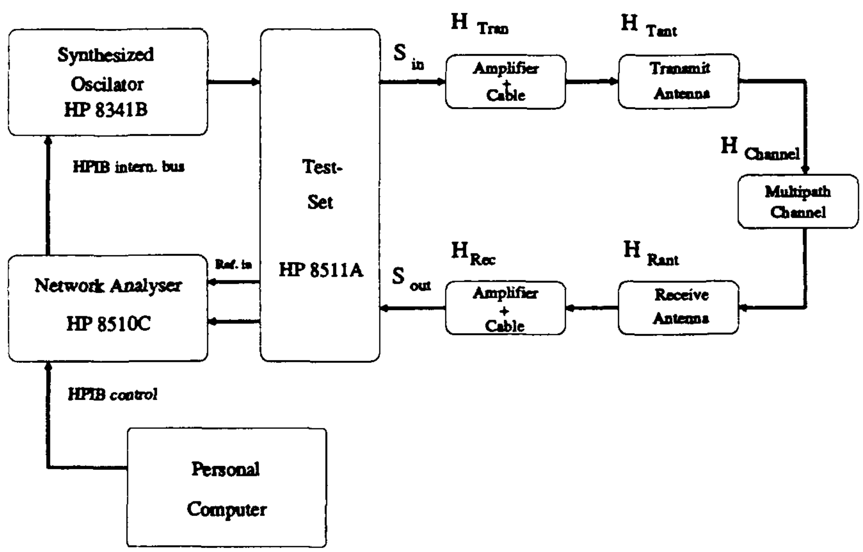


Fig 4.1: Set-up for indoor measurements.

The measurement set-up consists of:

- HP 8510C Network Analyser,
- HP 8341B Synthesized Sweeper,
- HP 8511A Testset,
- Antennas,
- Power amplifier(s),
- Preamplifier(s).
- PC-controller

The antennas that are used, are bi-conical antennas. This type of antenna is omnidirectional and vertically polarized. These antennas are chosen for the measurements because of the large bandwidth (and constant impedance over a large frequency range).
The antennas have been dimensioned for each frequency band so that the characteristics are about the same for all frequency bands. The beamwidth in the vertical plane is as large as possible: 110°, with about constant gain of -0.8 dB over the bandwidth of interest.
A more detailed description of the antenna design is given in Appendix A.

For the measurements a certain distance between transmitting and receiving antenna is required. Coherence between the input and ouput signals is achieved by connecting the antennas by cable to the Testset (no down conversion).
A problem with coaxial cable is that the attenuation at the frequencies used, is very high. This can be partly compensated by using power- and preamplifiers, but still the loss and price of the cable limit the maximum distance between transmitting and receiving antenna. The coaxial cable that was used, is the Sucoflex 106A cable which has the following loss characteristics:

- 2.4 GHz: 0.40 dB/m,
- 4.75 GHz: 0.75 dB/m,
- 11 GHz: 1.0 dB/m.

The total length of cable available, was about 30 m divided over the transmit and receive branches.

In Appendix B the results of link budget calculations are given. The minimum required received signal power at the testset is -90 dBm for SNR [illegible] 20 dB. The path losses that are allowed are then: 123 dB, 139 dB and 123 dB at 2.4 GHz, 4.75 GHz and 11.5 GHz respectively.
In Appendix B also the measurement setups at the three frequency bands with the amplifiers used, are given in more detail.

4.2 Measurements performed and data storage

The actual measurement consists of coherent amplitude/phase measurements at 801 equidistant frequency points (this is the maximum number which can be performed by the Network Analyser). The Network Analyser directly calculates the FFT of this series of measurement data, which results in the complex impulse response.
The output data is:

- the frequency response: a series of frequency, amplitude and phase values,
- the impuls response: a series of time, amplitude and phase values.

The data is transfered to an IBM-compatible computer in LOTUS format.

4.3 Parameters to be measured

The measurement parameters at 2.4 GHz, 4.75 GHz and 11.5 GHz are tabulated in the following:

- 2.4 GHZ

Centre frequency	:	2.4 GHz
Measurement bandwidth	:	0.5 GHz.
Time resolution	:	3 ns.
Unambiguous range	:	480 m ($\tau = 1.6\ \mu s$).

- 4.75 GHZ

Centre frequency	:	4.75 GHz
Measurement bandwidth	:	0.5 GHz.
Time resolution	:	3 ns.
Unambiguous range	:	480 m ($\tau = 1.6\ \mu s$).

- 11.5 GHZ

Centre frequency	:	11.5 GHz
Measurement bandwidth	:	1.0 GHz.
Time resolution	:	1.5 ns.
Unambiguous range	:	240 m ($\tau = 0.8\ \mu s$).

From the calculated values as given in figure 2.2, 2.3 and 2.4 and the maximum allowable path loss which result from the linkbudget calculations (Appendix B), the maximum range is assessed. This is also a measure for the range ambiguity which must be taken into account during the measurements.

In the following the path-loss law exponent a is assumed to be $a \approx 3$, and an extra margin of 20 dB for detection of low power multipath signal (down to 20 dB with respect to the strongest signal) is taken into account. With these assumptions an overview of the expected maximum distances is

made for the three frequency bands. The unambiguous range is calculated with the measurement parameters as given above.

- 2.4 GHz

  Maximum allowable loss : 116 - 20 = 96 dB

  Maximum detection range : 80 m

  R_{unamb} : 480 m

- 4.75 GHz

  Maximum allowable loss : 133 - 20 = 113 dB

  Maximum detection range : 200 m

  R_{unamb} : 480 m

- 11.5 GHz

  Maximum allowable loss : 116 - 20 = 96 dB

  Maximum detection range : 30 m

  R_{unamb} : 240 m

For the 2.4 and 11.5 GHz bands the unambiguous range is large enough compared to the expected propagation range. For the 4.75 GHz band however, the transmitted power should be decreased with ≈ 20 dB. Then the maximum detection range decreases down to 100 m.

4.4 Calibration of the measurement system

The total measurement system is built up with different elements each having their own frequency response. We are only interested in the response of the radio multipath channel. In order to be able to measure the unknown response of the radio channel, the response of the other elements like amplifiers, cables and attenuators must be determined. This can be achieved by calibrating the system.

The calibration set-up is schematically depicted in figure 4.2.

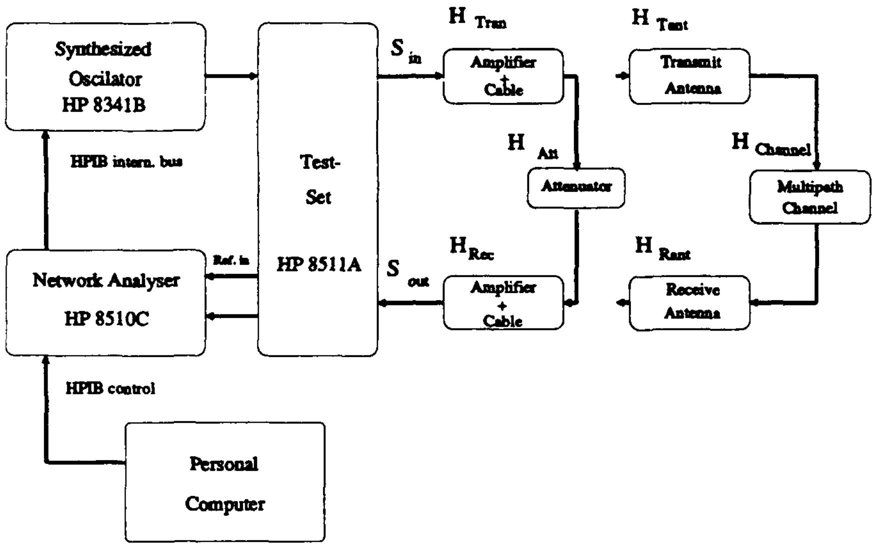


Fig. 4.2: Diagram of the calibration set-up.

The calibration of the measurement system is performed in the following way. The radio channel plus both antennas are directly connected together. Care must be taken not to overload these inputs in order to keep the system linear and to prevent it from damage. In order to achieve the correct signal levels at the preamplifier and the signal input of the analyser, the connection is made via a calibrated attenuator. The response measured in this way must be corrected for the influence of the calibrated attenuator.

The measured response without calibration is:

$$H_{Nocal} = S_{out}/S_{in} = H_{Tran} \cdot H_{Tant} \cdot H_{Channel} \cdot H_{Rant} \cdot H_{Rec} \tag{4.1}$$

This shows directly that this response is determined by the multipath channel and also by measurement system components.

The measured response during a calibration measurements is:

$$H_{Cal} = S_{out}/S_{in} = H_{Tran} \cdot H_{Att} \cdot H_{Rec} \tag{4.2}$$

The calibration values for all frequencies points that are measured are stored and used to correct the radio channel measurement results. This calibration procedure has to be carried out for all frequency bands.

The measured response with calibration now becomes (fig. 4.1):

$$H_{Meas} = H_{Nocal}/H_{Cal} = H_{Tant}.H_{Channel}.H_{Rant}/H_{Att} \tag{4.3}$$

H_{Att} is known, so the measured response is the combined response of the antennas and the channel.
When the system is calibrated in this way, a number of unknown effects are still not included.

1. Variations of cable parameters

At the high frequencies used, the responses of the cables may change when the cables are replaced or bent. It is assumed that this will not significantly influence the measurement results. The changes that can be expected by replacing the cable are linear effects in the order of 0.1 dB in amplitude and several mm's in effective length. These errors, which cannot we calibrated out, do not significantly affect the relative amplitude, phase and delay time of the multipath components to be measured.

2. The influence of the antennas

The antennas that are used are wideband antennas. This means that there are only small gain variations over the frequency band of interest. The gain variations that can be expected for one antenna (for the total system this value must be doubled) are:

- 2.40 GHz: $\Delta G = 0.9$ dB
- 4.75 GHz: $\Delta G = 0.46$ dB
- 11.50 GHz: $\Delta G = 0.38$ dB

The influence of this variation has not been taken into account in the calibrations described above.

4.5 Measurement scenario for the indoor environment

In this pargraph the measurement scenario for the indoor measurements will be described. The measurement environment can be classified as an indoor office environment. The measurements are distinguished in the following cases:

1. Transmitter and receiver antenna in a 3-window room
2. Transmitter and receiver in adjacent rooms, with one or two walls in between
3. Transmitter and receiver in a large discussion room
4. Transmitter in hallway and receiver in a 2-window room
5. Transmitter and receiver in a 3-window room with people in different positions.

In the following we will discuss the measurement protocol and the 5 cases as mentioned above, in further detail.

4.5.1 Measurement protocol

The measurement protocol includes the measurement positions in a cluster, the administration and storage of the results.

- Cluster definition

In most cases the measurements are conducted as a cluster of measurements at a certain position. A cluster consists of six measurements, which positions are located on a circle with a 12.5 cm diameter. The positions on the circle have a distance of $\lambda/2$ at 2.4 GHz, λ at 4.75 GHz and 2λ at 11.5 GHz. A larger cluster would be likely, however then the total number of measurements would become too large. In figure 4.3 the cluster dimensions are depicted.

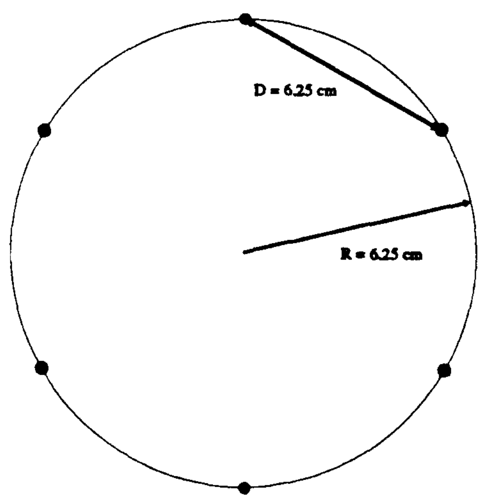


Fig. 4.3: Drawing of the cluster dimensions.

- Measurement sytem control and storage of the results

The measurements are performed with the network analyser setup, as described in the previous chapter. The system is controlled by LabWindows running on an AT-computer. This control program selects the chosen frequency range and the calibration which belongs to it, and initializes the system. The measurement results are stored. The name of the file can be given and additionally a number is assigned to the measurement. In a logbook additional information on frequency, cluster location, position in a cluster, transmitter antenna height and measurement environment are stored automatically with each measurement.

The measurement data which is stored, consists of the measured (complex) frequency spectrum and the (complex) power-delay profile. The results are corrected with the calibration results.
Before the measurement data can be used for calculations, the special Hewlett Packard binary format has to be converted to the regular ASCII format that can be read by (for example) the LOTUS software. Conversion software to perform this operation has been written.

4.5.2 Measurement environments

The measurements have been performed in an office environment at TNO-Physics and Electronics Laboratory (FEL-TNO). Within this laboratory different environments are used. Most of the locations are in the 3G hall way, which is depicted in figure 4.4

In the discussion on the measurements the following variables are used:

P_R = number of positions of the receiver antenna in the room

P_{TR} = number of positions of the transmitter antenna in the room

C = number of measurements in the cluster on position P_n of the receiver antenna.

A = number of transmitter antenna heights

F = number of frequencies

1. Transmitter and receiver antenna in a 3-window office room

These measurements have been conducted in room 3G11. The room dimensions are length = 5.6 m, height = 3.5 m and width = 5 m.
The receiver antenna height was 1.5 m. The transmitter antenna heights were 1.5 and 3 m. The position of the transmitter antenna was about in the middle of the room.
Measurements were taken at 10 positions and 3 frequencies. The cluster at each point consisted of 6 measurements 6.25 cm apart as is discussed before.

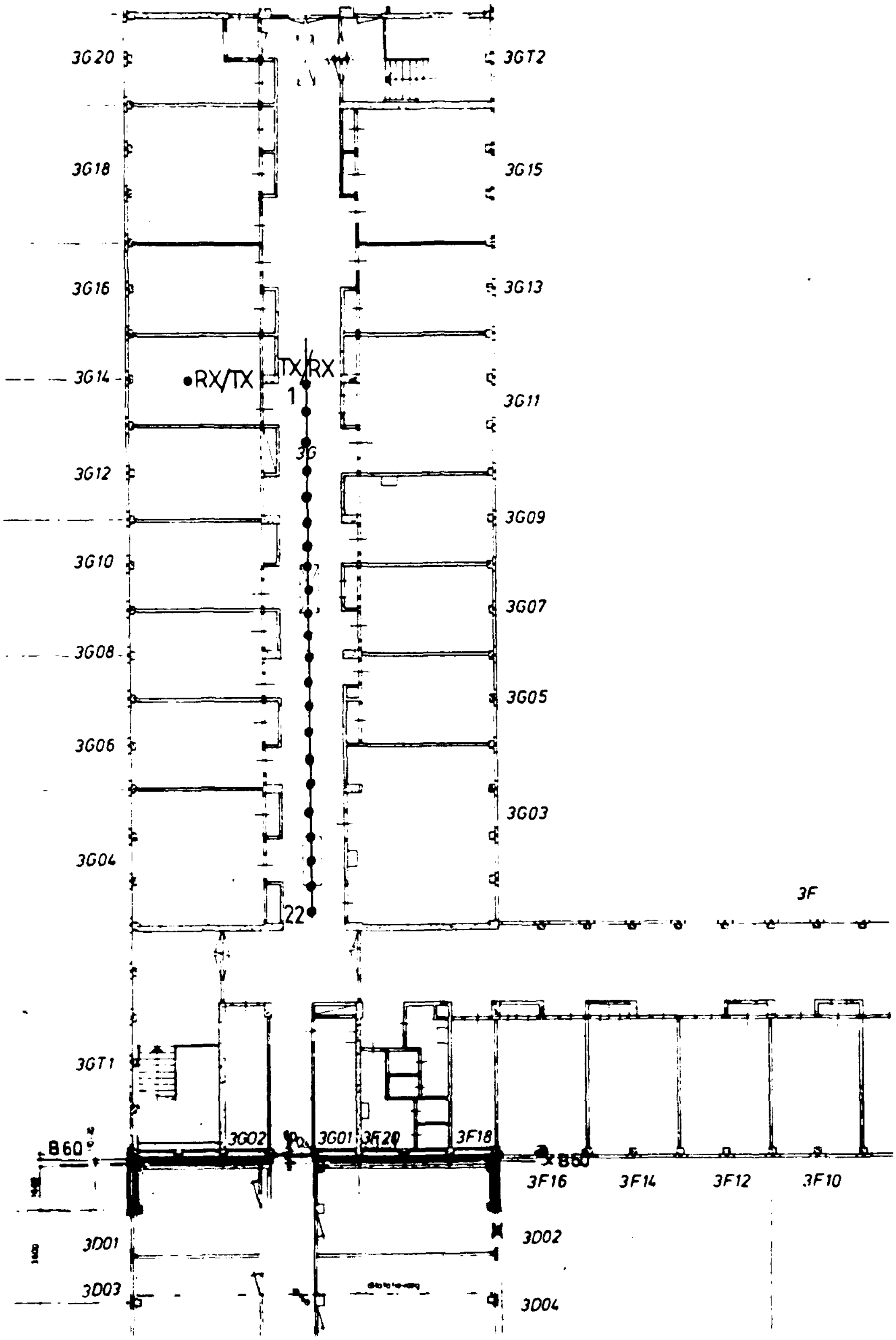


Fig. 4.4: Schematic overview of the 3G hall way.

In figure 4.5 an overview of room 3G11 with the measurement positions is given.

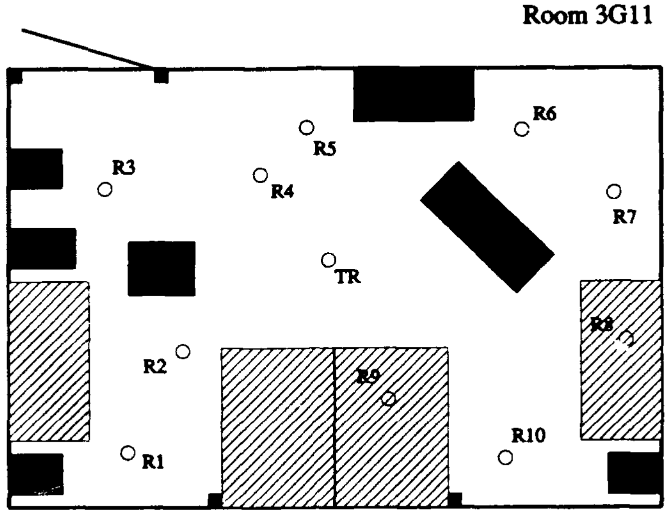


Fig. 4.5: Schematic overview of room 3G11 and the measurement positions.

P_{TR}	=	1	F	=	3
P_R	=	10	A	=	2
C	=	6			

The total number of measurements: 360.

The distances between the receiver positions and the transmitter position:

R1	-	TR:	2.1 m	R6	-	TR:	2.3 m
R2	-	TR:	1.1 m	R7	-	TR:	2.4 m
R3	-	TR:	1.1 m	R8	-	TR:	2.4 m
R4	-	TR:	1.7 m	R9	-	TR:	1.5 m
R5	-	TR:	2.1 m	R10	-	TR:	2.3 m

2. Transmitter and receiver in different rooms

These measurements have been conducted in room 3G14 and the two adjacent room 3G10 and 3G12. All three room are two window room with the same dimensions: length = 3.6 m, height = 3.5 m, width = 5 m.

The receiver antenna was placed in 3G14 at a height of 1.5 m. The transmitter was positioned in 3G10 and 3G12. Its height was 1.5 and 3 m. Measurements have been taken at 2 positions for the receive antenna and at 3 frequencies. The cluster at each point consisted of 6 measurements 6.25 cm apart.
The measurement site is shown in figure 4.6.

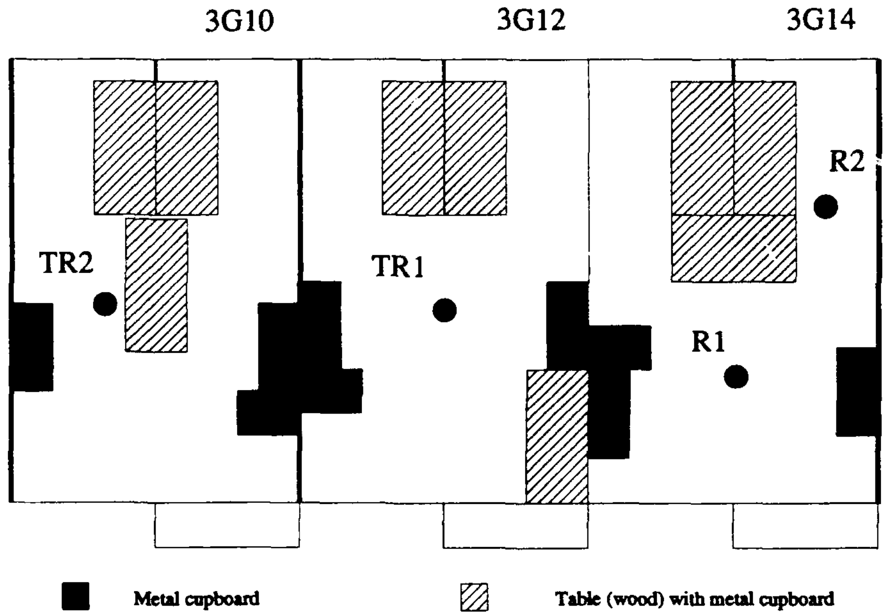


Fig. 4.6: Receiver and transmitter in different rooms.

P_{TR}	=	2	F	=	3
P_R	=	2	A	=	2
C	=	6			

The total number of measurements: 144.

The distances between receiver and transmitter are:

R1	-	TR1: 3.7 m	R1	-	TR2: 7.8 m
R2	-	TR1: 4.8 m	R2	-	TR2: 9.0 m

3. Transmitter and receiver in a large discussion room

These measurements have been conducted in the large discussion room 3C10 with dimensions: length = 25 m, height = 3.5 m and width = 10 m. The receiver antenna was placed at 10 different

positions, as depicted in figure 4.7, at a height of 1.5 m. The transmitter antenna was placed at a fixed position about in the middle of the room at a height of 3 m. At the 10 receiver positions measurements have been conducted at 3 frequencies. The cluster at each point consisted of 6 measurements 6.25 cm apart.

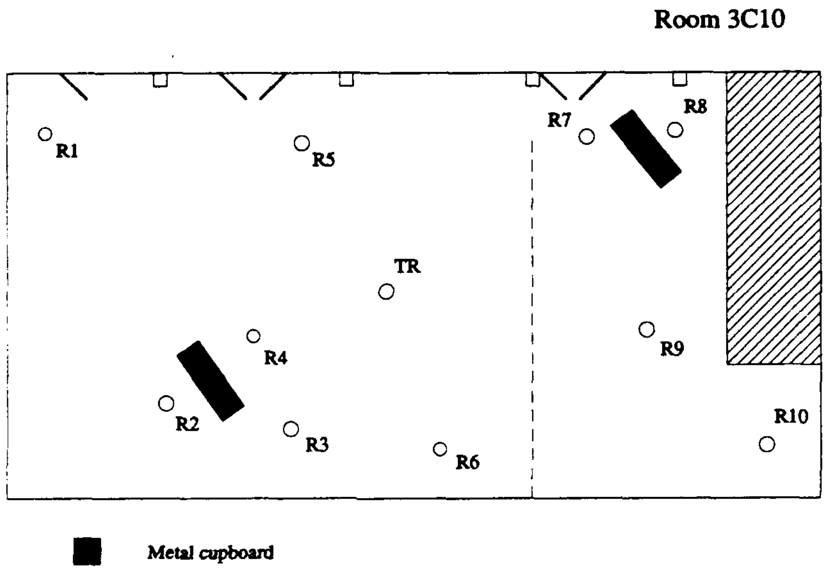


Fig 4.7: Measurement positions in 3C10.

P_{TR}	=	1	F	=	3
P_R	=	10	A	=	1
C	=	6			

The total number of measurements: 180.

The distances between the transmitter and receiver positions are:

R1	-	TR:	12.1 m	R6	-	TR:	4.9 m
R2	-	TR:	8.8 m	R7	-	TR:	6.4 m
R3	-	TR:	6.5 m	R8	-	TR:	9.5 m
R4	-	TR:	6.2 m	R9	-	TR:	9.7 m
R5	-	TR:	4.7 m	R10	-	TR:	12.9 m

4. Transmitter in the 3G hallway and receiver in 3G14.

These measurements have been conducted in room 3G14 and the 3G hallway. The hall way is 35 m long, 3 m wide and 3.5 m heigh. The receiver antenna height was at 1.5 m. The transmitter antenna height was at 3 m on 22 different positions in the hallway. Measurements have been taken at 1 position in room 3G14 at 3 frequencies.

The transmitter antenna was about in the middle of the hallway. The measurement positions are depited in figure 4.4.

The measurements are repeated with interchanged transmitter and receiver positions.

P_{TR}	=	20	F	=	3
P_R	=	1	A	=	1
C	=	1			

The total number of measurements: 120.

The distances between the positions in the hallway and 3G14 are:

P1:	3.6 m	P9:	9.6 m	P16:	16.3 m
P2:	4.0 m	P10:	10.6 m	P17:	17.3 m
P3:	4.6 m	P11:	11.5 m	P18:	18.3 m
P4:	5.3 m	P12:	12.5 m	P19:	19.3 m
P5:	6.1 m	P13:	13.4 m	P20:	20.3 m
P6:	7.0 m	P14:	14.4 m	P21:	21.3 m
P7:	7.8 m	P15	15.4 m	P22:	22.3 m
P8:	8.6 m				

5. Transmitter and receiver in a 3-window room with people in different positions.

These measurements again have been conducted in room 3G11. The receiver antenna height was at 1.5 m. The transmitter antenna height is at 1.5 and 3 m. Measurements were taken at one position of receiver and transmitter antenna, and with 3 frequencies. The transmitter and receiver antenna were placed as depicted in figure 4.8. For each frequency the empty room response is measured. 10 measurements were carried out with 6 persons present in the room. During 5 of the measurements the direct path was unobstructed (LOS), for the other 5 measurements the direct path was deliberately obstructed (OBS).

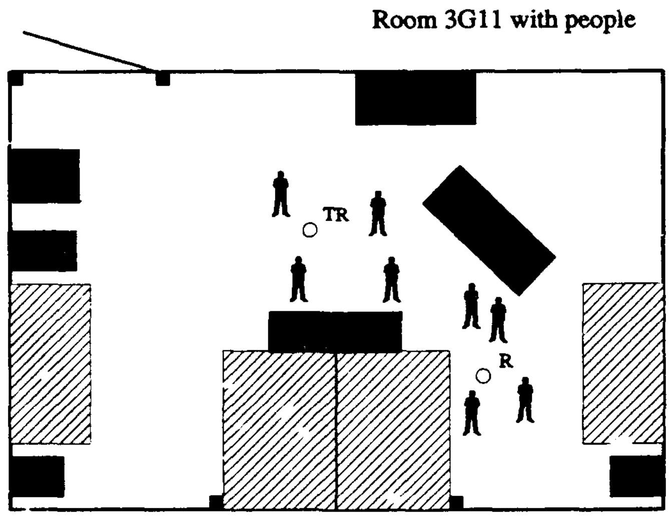


Fig. 4.8: Measurement situation in 3G11 (with people).

Number of people configurations = 10

P_{TR}	=	1	C	=	1
P_R	=	1	F	=	3
P	=	1	A	=	2

The total number of measurements: 60.

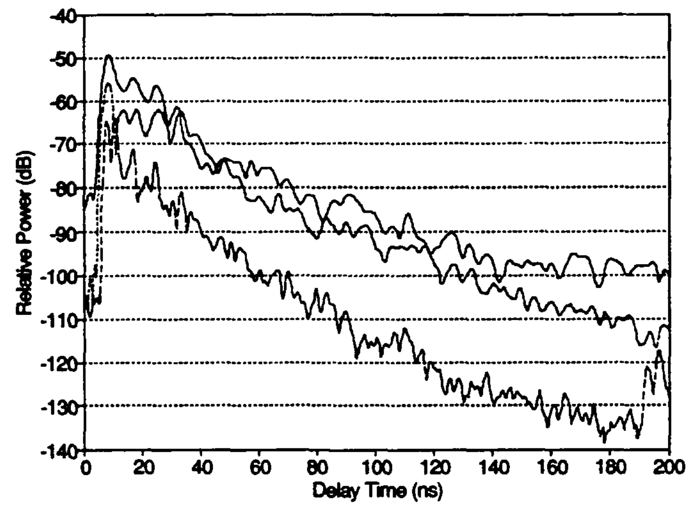
5 RESULTS OF THE INDOOR MEASUREMENTS

In this chapter the results on path-loss and RMS delay time spread τ_{RMS}, which are cue parameters in radio communications system design, are presented. These parameters have been computed from the indoor measurement results: power delay profile (PDP) and frequency response, [17].

5.1 Power delay profile and frequency response

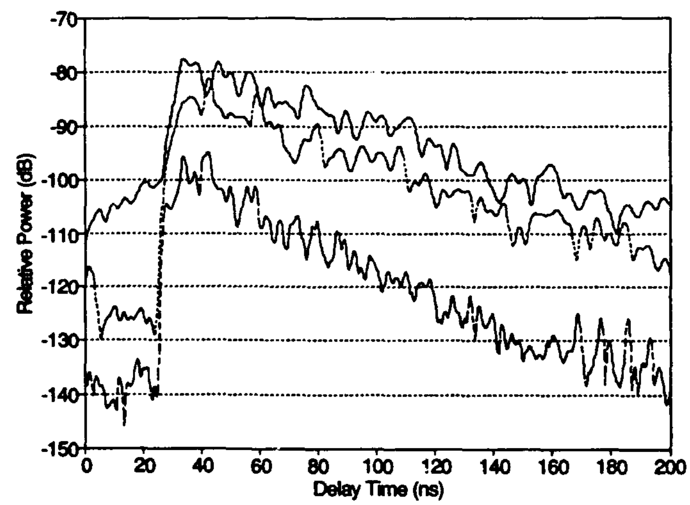
The power-delay profile and the frequency response of the radio channel are the basic data, collected during the measurements, from which the path-loss and delay-time spread results have been computed.

In figures 5.1 and 5.2 two plots are given of the averaged PDP in a LOS and an OBS situation at 2.4 GHz, 4.75 GHz and 11.5 GHz. The results are the power averaged values over the corresponding cluster measurement results. The plots clearly show the existance of multipath.
In figure 5.3 the averaged PDP at 2.4 GHz is given for the same position as in figure 5.1, together with one specific path from that cluster. We see here that the averaged PDP shows the same paths, however in a more smoothed way.
In LOS situations the direct path is clearly seen, it is the first path which is also the strongest. The following paths that arrive, gradually lose strength due to the larger distance that is traversed and the reflection coefficient of reflective objects. In OBS situations the first arriving paths have about equal strength.



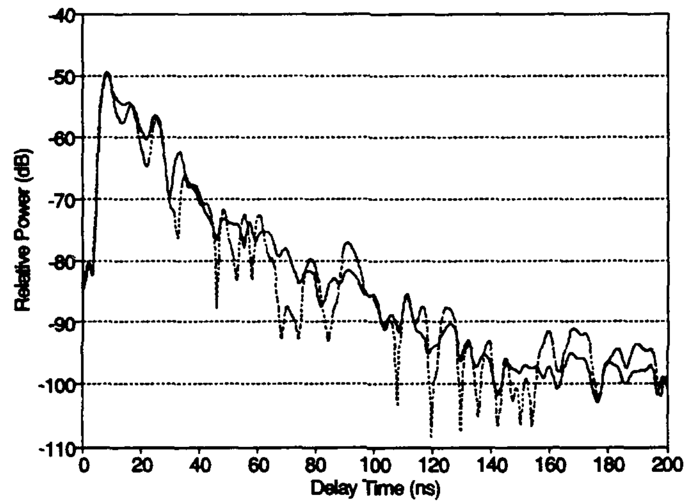
____ 2.4 GHz ___ 4.75 GHz .... 11.5 GHz

Fig 5.1: Averaged Power Delay Profiles in a LOS situation (position 1 in 3G11) at 2.4, 4.75 and 11.5 GHz.



____ 2.4 GHz ___ 4.75 GHz .... 11.5 GHz

Fig. 5.2: Averaged Power Delay Profiles in an OBS situation (position 1 3G10 <--> 3G14) at 2.4, 4.75 and 11.5 GHz.



____ Averaged over 6 cluster measurements ..... A single cluster measurement

Fig. 5.3: Power Delay Profile in a LOS situation (position 1 in 3G11) at 2.4 GHz.

The averaged PDP over 6 cluster positions for LOS situations clearly shows an exponential shape at all three frequencies. The decay at 2.4 GHz and 4.75 GHz is about the same, whereas the decay at 11.5 GHz is faster.

In OBS situations it was found that the PDP tends to a more linear shape as is shown in figure 5.2. The path distribution influences the behaviour of the channel. This however, will not be analysed further in a theoretical way here.

The frequency responses of the corresponding positions at 2.4 GHz are given in figures 5.4 and 5.5.

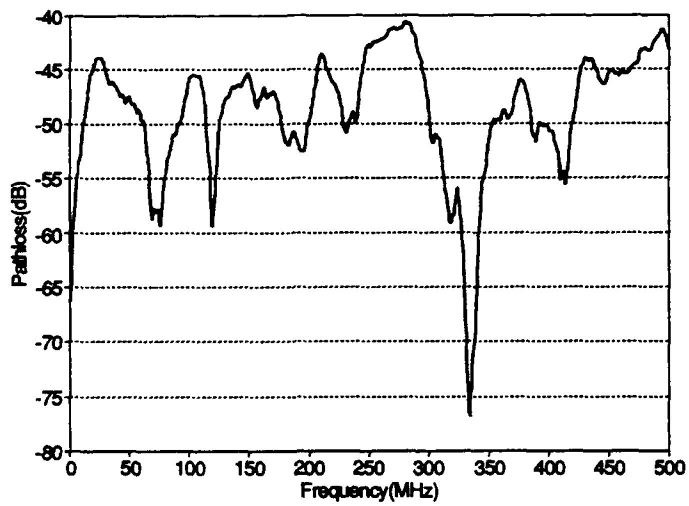


Fig. 5.4: Frequency response in a LOS situation (position 1 in 3G11) at 2.4 GHz.

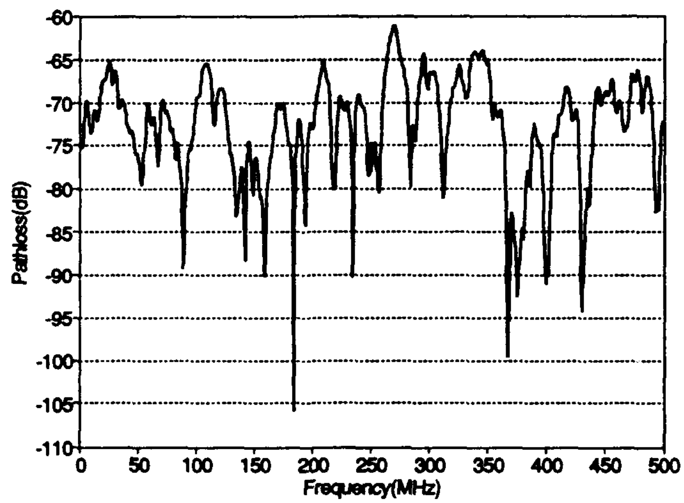


Fig. 5.5: Frequency response in an OBS situation (position 1 3G10 <--> 3G14) at 2.4 GHz.

The frequency responses show that deep fades exist for both LOS and OBS situations. However, the number of deep fades is larger for the obstructed situation. Furthermore it is shown that the range over which the frequency spectrum can be assumed constant is smaller for the obstructed situation.

5.2 Path-loss law

The path-loss has been computed as the average of the path-loss over the measured frequency band (0.5 GHz bandwidth at 2.4 and 4.75 GHz and 1.0 GHz bandwidth at 11.5 GHz).
To determine the path-loss law the measured results for all situation have been used. The path-loss results at 2.4, 4.75 and 11.5 GHz are treated separately for LOS and OBS situations.

In the following the attenuation of the radio signal as function of distance is given relative to the loss at 1 m distance. The path-loss results are given in the attenuation-distance profiles of figures 5.6 - 5.11.

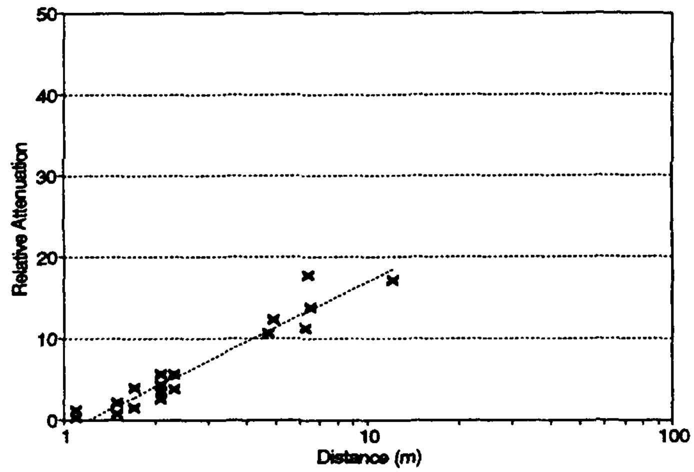


Fig. 5.6: Attenuation-distance profile (relative to the attenuation at 1 m) for LOS at 2.4 GHz.

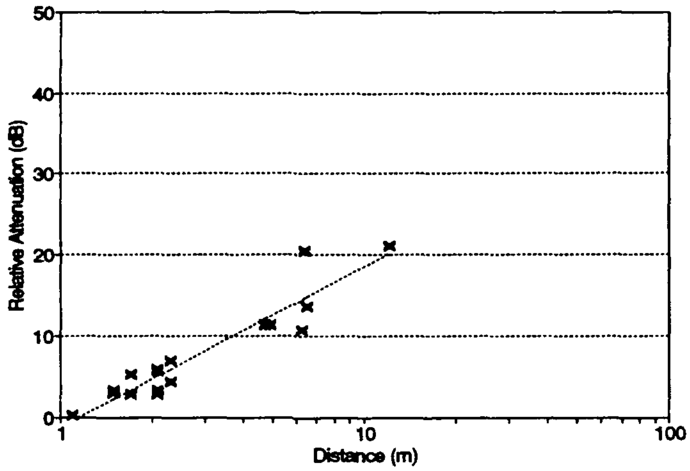


Fig. 5.7: Attenuation-distance profile (relative to the attenuation at 1 m) for LOS at 4.75 GHz.

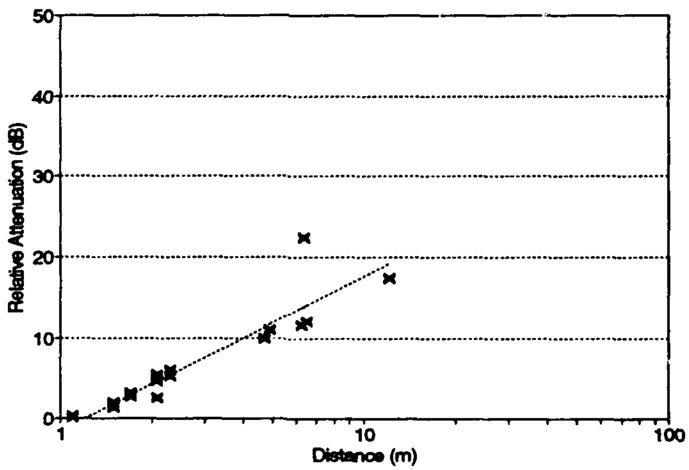


Fig. 5.8: Attenuation-distance profile (relative to the attenuation at 1 m) for LOS at 11.5 GHz.

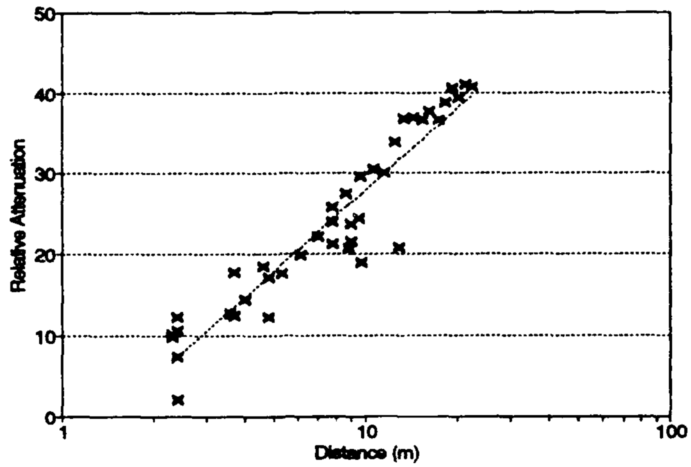


Fig. 5.9: Attenuation-distance profile (relative to the attenuation at 1 m) for OBS at 2.4 GHz.

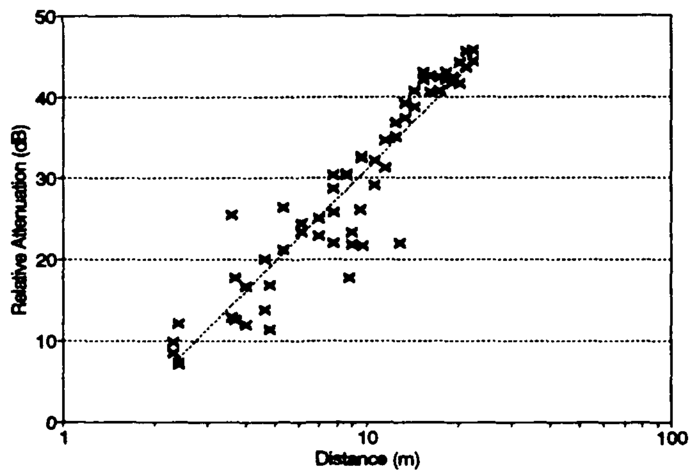


Fig 5.10: Attenuation-distance profile (relative to the attenuation at 1 m) for OBS at 4.75 GHz.

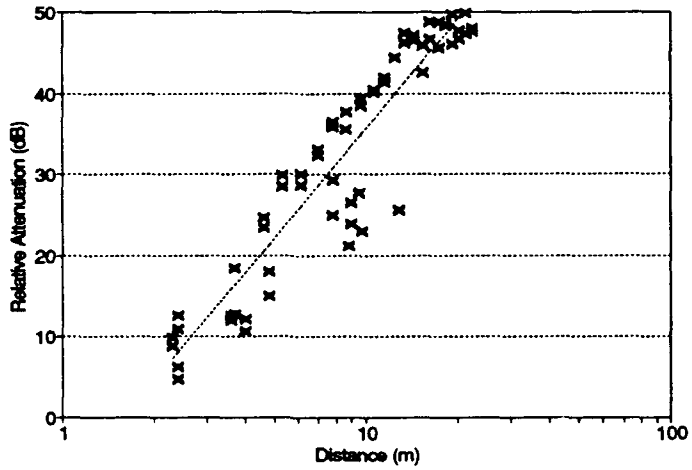


Fig. 5.11: Attenuation-distance profile (relative to the attenuation at 1 m) for OBS at 11.5 GHz.

The path-loss law has been computed from the measurement results by fitting a straight line through the attenuation-distance profile. The simple model that comes with this regression is described by 5.1:

$$\text{Rel. Attenuation} = S(d_0) + 10.a.\log(d/d_0) + b \qquad (5.1)$$

Rel. Attenuation is the path-loss relative to the path-loss value $S(d_0)$ at $d_0 = 1$ meter, a is the path-loss exponent, b the value of the regression line at 1 meter distance and d is the distance between transmitter and receiver antenna. The measured value of $S(d_0)$ is 43.1 dB, 48.4 dB and 57.6 dB at 2.4 GHz, 4.75 GHz and 11.5 GHz respectively.

In Table I the values for a, b and σ_L (RMS error of the measured values w.r.t. the "simple model"), are given for LOS and OBS situations at the three frequencies.

Table I: Results of linear regression for three frequencies.

Frequency	Location	a	b (dB)	σ_L (dB)
2.4 GHz	LOS OBS	1.86 3.33	-1.6 -5.4	1.6 3.6
4.75 GHz	LOS OBS	1.98 3.75	-1.2 -6.5	2.0 4.1
11.5 GHz	LOS OBS	1.94 4.46	-1.7 -8.9	2.3 5.0

From the figures 5.6 - 5.11 and Table I the following can be concluded.

For LOS situations the path-loss exponent values at all three frequencies are very close to the expected value for free-space propagation a = 2.0. The values for b are slightly negative, but very close to 0 dB as expected. The RMS error σ_L is small (< 2.5 dB), however, increases with frequency.

For OBS situations the path-loss exponent values increase with frequency (3.3, 3.8 and 4.5 at 2.4 GHz, 4.75 GHz and 11.5 GHz respectively). The b values are becomming increasingly negative with increasing frequency (-5.4 dB, -6.5 dB and -8.9 dB at 2.4, 4.75 and 11.5 GHz respectively). The RMS error σ_L increases with frequency.
It must be concluded that the simple model is not accurate enough for OBS paths. The same effect as shown in the figures 5.9 - 5.11 results when the path-loss exponent a = 2.0 is used, with attenuation jumps at certain distances. This more complicated model is given in (2.19) and described in [9, 10]. An example of a single path, described with this model, is given in figure 5.12. Here attenuation jumps of 6, 8, 5 and 7 dB are assumed due to walls and other obstacles. The distances of the obstacles are 3, 6, 9 and 14 m.

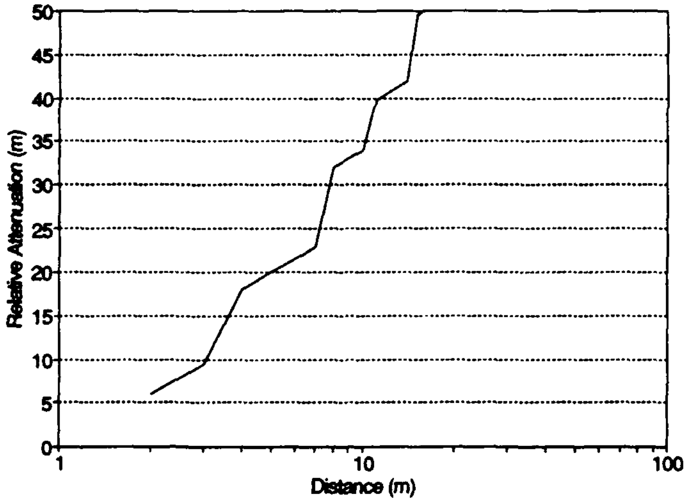


Fig. 5.12: Attenuation-distance profile for the model with attenuation jumps due to obstacles (eg. walls).

For this single path the path-loss exponent, as calculated with regrassion analysis, is a = 4.6 and b = -8.6. At first glance this model makes it possible to explain the increase of a and the negative value of b when the path contains obstacles. The first results of using this model for attenuation prediction in the literature look very promissing, however, this model has not been validated carefuly yet. More detailed information on attenuation factors for different materials at different frequencies are required, as well as further validation measurements.

Conclusions

From these results it can be concluded that the simple model gives quite good results for LOS situations, in OBS situations however, the attenuation predictions are not very accurate. An improvement is suggested by assuming discontinuous attenuation jumps at the distance of an obstacle. This model is proposed in the literature, but has not been validated yet.

5.3 The influence of people on path-loss

In room 3G11 (3-window office room) measurements have been performed in the presence of people to investigate the influence of people located at different positions in the room. The measurement results with people present are compared with the results for the empty room.

In Table II the results at 2.4 GHz, 4.75 GHz and 11.5 GHz are given relative to the empty room (no people present in the room) with the transmitter antenna at 1.5 and 3 m. Also the standard deviation σ of this value is given.
LOS means here that the people do not obstruct the direct path between transmitter and receiver.
In the OBS situation the direct path is obstructed by people.
For each situation 5 measurement have been carried out with the people in different randomly chosen positions.

Table II: Comparison of excess attenuation in office room due to people present in the room for LOS and OBS situations at 2.4 GHz, 4.75 GHz and 11.5 GHz

Frequency	LOS / OBS	Height	Rel. Att (dB)	σ (dB)
2.4 GHz	LOS	1.5 m 3.0 m	-0.33 0.24	0.3 0.3
	OBS	1.5 m 3.0 m	4.84 2.73	1.8 2.3
4.75 GHz	LOS	1.5 m 3.0 m	0.64 -0.3	1.1 0.8
	OBS	1.5 m 3.0 m	5.35 1.46	3.7 1.4
11.5 GHz	LOS	1.5 m 3.0 m	0.19 0.28	0.6 0.8
	OBS	1.5 m 3.0 m	4.33 3.59	1.5 0.6

Table II shows that the presence of people in a room, as long as they are not obstructing the direct path (LOS) between transmitter and receiver, only slightly influences the received power level (less than 1 dB). In some LOS situations the presence of people has a small positive effect, in other cases a small negative effect (a fraction of a dB). Obstruction of the direct path has a clear negative effect on the received power level: the attenuation increases compared to the empty room. The direct path which contains most of the signal power has disappeared. For the transmitter antenna at 1.5 m, the exess attenuation is 4 - 5.5 dB, when the antenna is at 3 m the exess attenuation becomes less: 1.5 - 3.5 dB.
For both, LOS and OBS situations, no clear difference between the three frequencies was found.

One should be careful with drawing general conclusions from these results since only a very limited number of configurations has been measured. Furthermore, the positions of the people were chosen at random because for each frequency it is practically impossible to reproduce the same spatial configuration.

Conclusions

The effects of people on path-loss, when compared to the results for an empty room, is marginal. For LOS situations the effect is negligible. When people obstruct the direct path (OBS), 4 - 5.5 dB extra attenuation was found on the average. No clear difference in behaviour was found for the three frequencies 2.4, 4.75 and 11.5 GHz.
Because of the small number of measurements, the interpretation of the results, as given here, should be handled with care.

5.4 RMS delay time spread

The RMS delay time spread τ_{RMS} is the second central moment of the Power-Delay Profile as defined by (2.7). This parameter is a measure for the dispersion of the radio channel, and can therefore be used to estimate the maximum usable bit rate for conventional data transmission techniques, as given by (2.10). For all measurement positions the RMS Delay spread has been calculated. The results are tabulated for LOS and OBS situations.
Tables III contains the results for LOS situations. The average values and standard deviation of the values of $\tau_{PM\Sigma}$ at three frequencies are given for different locations and different antenna heights. In Table IV the same results are given for OBS situations.

Table III: RMS Delay Spread (τ_{RMS}) and standard deviation (σ_{RMS}) of all LOS measurements for two transmitter antenna heights and three frequencies (τ_{RMS} and σ_{RMS} in ns).

Situation	2.4 GHz				4.75 GHz				11.5 GHz			
	τ_{RMS}		σ_{RMS}		τ_{RMS}		σ_{RMS}		τ_{RMS}		σ_{RMS}	
	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m
3G11	7.3	8.0	1.4	2.2	8.5	8.5	2.4	1.4	4.6	6.2	1.3	0.9
3G11-pers	8.3	7.4	0.5	1.6	11.8	7.9	1.0	1.2	5.6	5.1	0.5	0.4
3C10	14.9	-	2.9	-	18.0	-	5.2	-	12.8	-	3.7	-
Hw&3G10	5.4	-	0.9	-	10.2	-	2.6	-	4.3	-	1.4	-

Table IV: RMS Delay Spread (τ_{rms}) and standard deviation (σ_{rms}) of all OBS measurements for two transmitter antenna heights and three frequencies (τ_{rms} and σ_{rms} in ns).

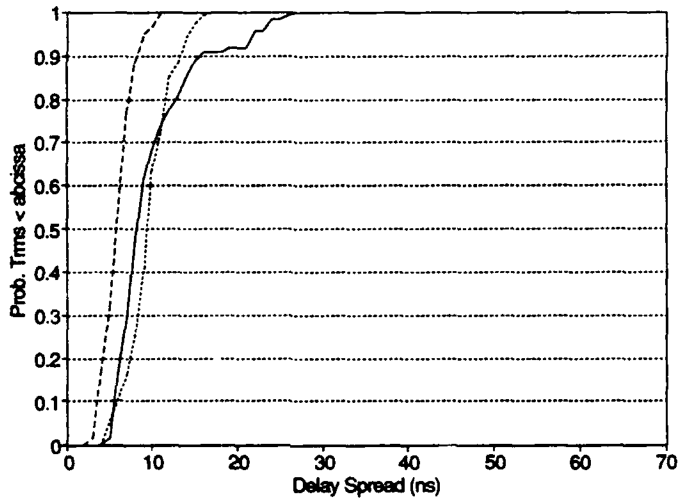
Situation	2.4 GHz				4.75 GHz				11.5 GHz			
	τ_{RMS}		σ_{RMS}		τ_{RMS}		σ_{RMS}		τ_{RMS}		σ_{RMS}	
	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m
3G11	12.4	17.3	2.5	7.2	11.6	12.4	2.3	2.5	6.5	7.9	1.2	2.1
3G11-pers	8.75	10.8	1.1	3.1	11.1	10.6	1.2	1.1	5.4	5.4	1.1	0.9
3G12/3G14	12.1	19.8	1.1	1.4	12.6	21.2	1.1	2.9	9.7	14.4	1.6	1.1
3G10/3G14	19.2	23.1	3.0	1.7	19.3	21.5	1.9	1.3	12.4	13.6	1.5	1.8
3C10	21.1	-	5.5	-	23.6	-	4.3	-	20.1	-	2.9	-
Hw/3G14	21.6	-	17.0	-	15.2	-	4.4	-	18.6	-	10.1	-

It can be seen from the Tables III and IV that τ_{RMS} is always minimum at 11.5 GHz, except in the hallway for some OBS paths. At 11.5 GHz, τ_{RMS} is at the average about 30% lower than τ_{RMS} at 2.4 GHz and 4.75 GHz. In general for LOS situations the height of the transitter antenna only slightly influences τ_{RMS}. However, reducing the transmitter antenna height from 3.0 m to 1.5 m yields an increase in τ_{RMS} and σ_{RMS} in OBS situations.

Large rooms (hall way and conference room) give large τ_{RMS} values due to large distances between reflective walls and objects. This observation is not always true for LOS paths (e.g., the hall way). When the transmitter and receiver are in adjacent rooms τ_{RMS} is less compared to when there is an empty room in between. This is possibly caused by the extra wall and reflective furniture.

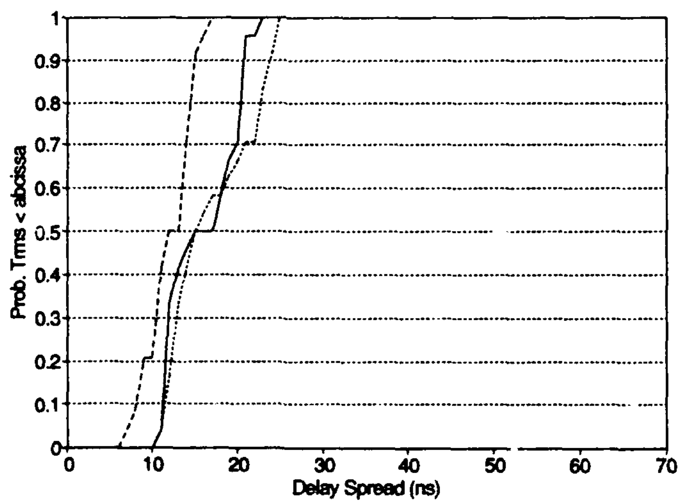
The measurements do not show a significant influence of people present in the room on τ_{RMS}, even when the direct path is obstructed.

In figures 5.13 - 5.17 the cumulative distribution functions of τ_{RMS} are given for different locations. These figures give a good indication of the variance in τ_{RMS} at different locations.



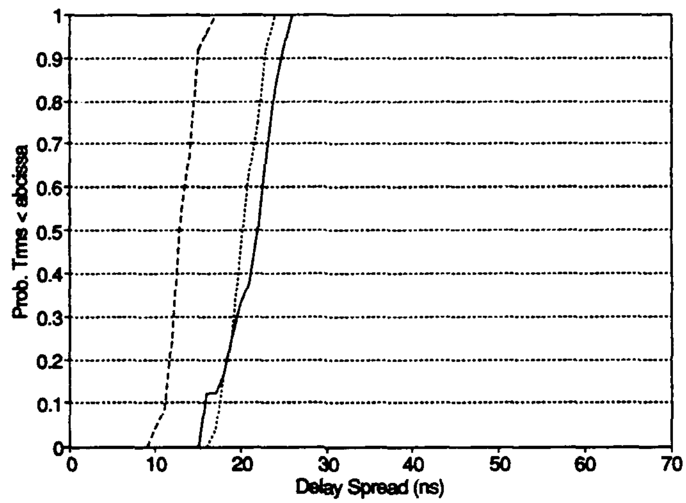
_____ 2.4 GHz .... 4.75 GHz _ _ _ 11.5 GHz

Fig 5.13: Cumu tive distribution function of τ_{RMS} for *three frequencies* with transmitter and receiver in an office room (3G11).



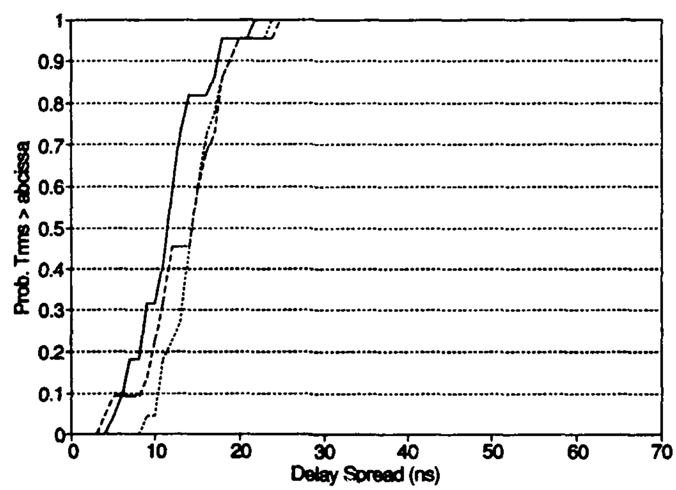
_____ 2.' GHz .... 4.75 GHz _ _ _ 11.5 GHz

Fig. 5.14: Cumulative distribution function of τ_{RMS} for three frequencies with transmitter and receiver in adjacent rooms (3G10 - 3G12).



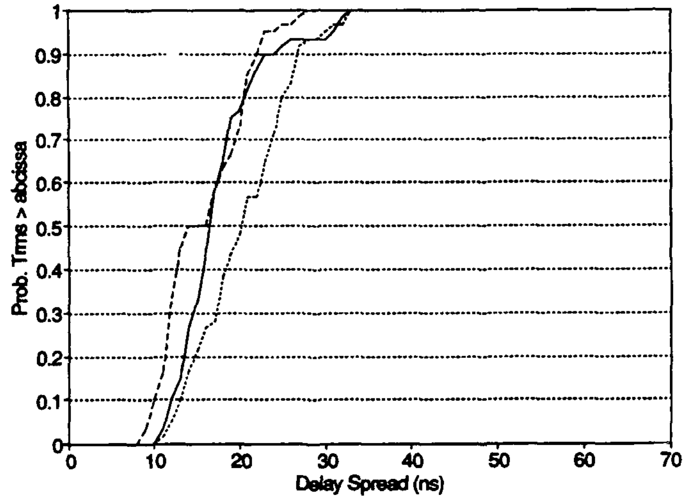
_____ 2.4 GHz .... 4.75 GHz _ _ _ 11.5 GHz

Fig 5.15: Cumulative distribution function of τ_{RMS} for three frequencies with transmitter and receiver at two rooms distance (3G12 - 3G14).



_____ 2.4 GHz .... 4.75 GHz _ _ _ 11.5 GHz

Fig 5.16: Cumulative distribution function of τ_{RMS} for three frequencies with the transmitter in the ball way and receiver in an office room (3G10).

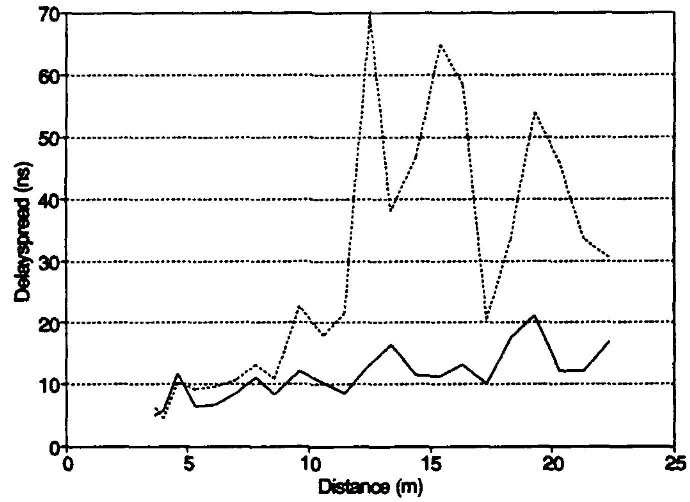


_____ 2.4 GHz .... 4.75 GHz _ _ _ 11.5 GHz

Fig. 5.17: Cumulative distribution function of τ_{RMS} for three frequencies with transmitter and receiver in the conference room (3C10).

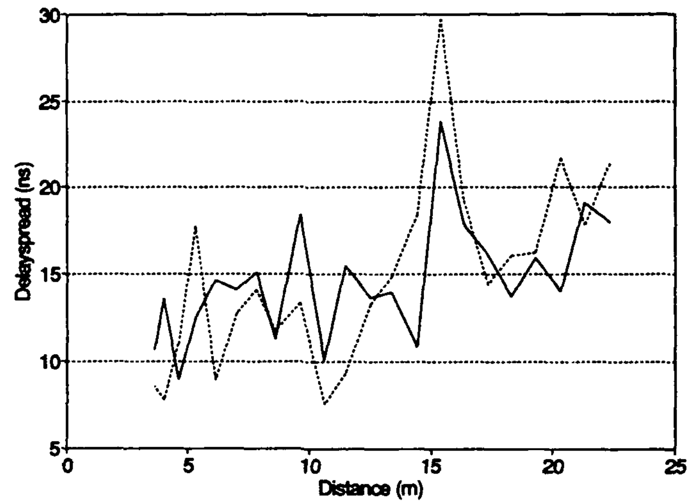
The cumulative distribution functions show the results of Tables III and IV in a different way. 11.5 GHz in general has the lowest τ_{RMS} value and variance of this value. τ_{RMS} at 2.4 GHz shows the largest variance. The distribution functions show that in general the value for τ_{RMS} is less than 30 ns.

This is not true for the situation with the receiver in the hall way and the transmitter in 3G14. These values also show a large spread. In figures 5.18 - 5.20 τ_{RMS} is given as function of distance for this situation.



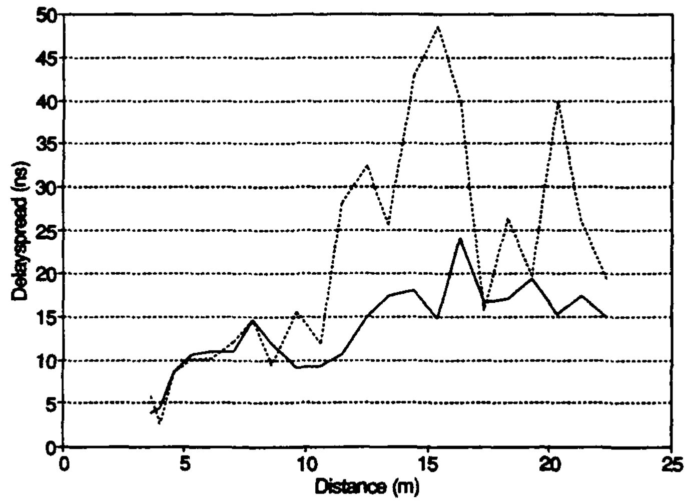
____ Transmitter in the hall way .... Receiver in the hall way

Fig 5.18: Plot of τ_{RMS} versus distance at 2.4 GHz. Transmitter and receiver are interchanged.



____ Transmitter in the hall way .... Receiver in the hall way

Fig 5.19: Plot of τ_{RMS} versus distance at 4.75 GHz. Transmitter and receiver are interchanged.



_____ Transmitter in the hall way .... Receiver in the hall way

Fig 5.20: Plot of τ_{RMS} versus distance at 11.5 GHz. Transmitter and receiver are interchanged.

Figures 5.18 - 5.20 show that the variance of τ_{RMS} in the hall way is large. Excessively large values of 70 ns were observed at some positions at about the middle of the hall way. The measurements with the receiver in the hall way show a larger τ_{RMS} than those with the transmitter in the hall way. This indicates clearly that the direct environment of the receiver has a greater impact on τ_{RMS} than the transmitter environment. The plots show that the spread of τ_{RMS} increases with distance. For 2.4 GHz the situation with the receiver in the hall way shows much larger τ_{RMS} values than the other frequencies.
At some positions large τ_{RMS} values are found at all frequencies.

Conclusions

The delay spread τ_{RMS} has been determined for different types of rooms with different dimensions. It was found that τ_{RMS} increases for the larger rooms, like the conference room and the hall way. In the hall way very strong fluctiations in τ_{RMS} were found.
With respect to the different frequencies it was found that τ_{RMS} at 11.5 GHz in most cases is significantly less ($\approx$ 30%) than τ_{RMS} at 2.4 GHz and 4.75 GHz, which are in general of the same order of magnitude.

In LOS situations the transmitter antenna height is of minor influence. Obstructed paths show increased τ_{RMS} values. The presence of people did not show any clear effect on τ_{RMS}.
During the measurements antennas with a wide opening angle were used. This leads to relatively low τ_{RMS} values compared to cases with high directive omnidirectional antennas [15].
The median values for τ_{RMS} at 2.4 and 4.75 GHz range from 10 - 20 ns (this implies a maximum bitrate of 12 - 25 Mbit/s)
The median values for τ_{RMS} at 11.5 GHz ranges from 5 - 15 ns (this implies a maximum bitrate of 16 - 50 Mbit/s)

5.5 Coherence bandwidth

The coherence bandwidth is defined as the -3 dB bandwidth of the frequency correlation function. The frequency correlation function is given in (2.11). Below a plot of the frequency correlation function is given.

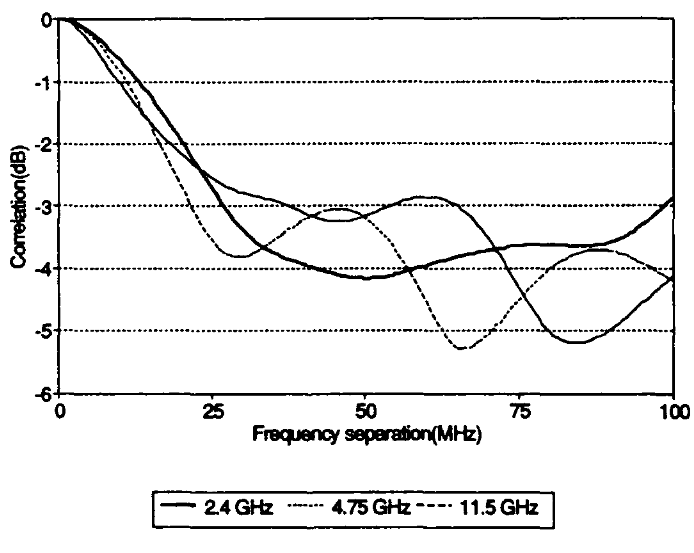


Fig 5.21: Frequency corre!ation function for three 3 frequencies with transmitter and receiver in the same room.

The shape of the frequency correlation function strongly depends on the characteristics of the multipath channel. In many situations the frequency correlation is an oscillating function. In case of a two paths channel with almost equal strength, this oscillating behaviour is very clear.

In Table V and VI the coherence bandwidth are given for LOS and OBS situation at three frequencies and for the different measurement locations.

Table V: Coherence Bandwidth for 2 antenna heights and three frequencies for LOS situations.

Location	2.4 GHz				4.75 GHz				11.5 GHz			
BW	6 dB Coh BW		3dB Coh BW		6 dB Coh BW		3 dB Coh BW		6 dB Coh BW		3 dB Coh	
	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m
3G11	146	155	90	94	120	143	91	100	362	166	198	140
3G11-pers	31	81	2	83	20	96	2	82	37	45	3	2
Conf.room	80	-	84	-	71	-	84	-	130	-	184	-
Hall way	199	-	75	-	106	-	98	-	500	-	0	-

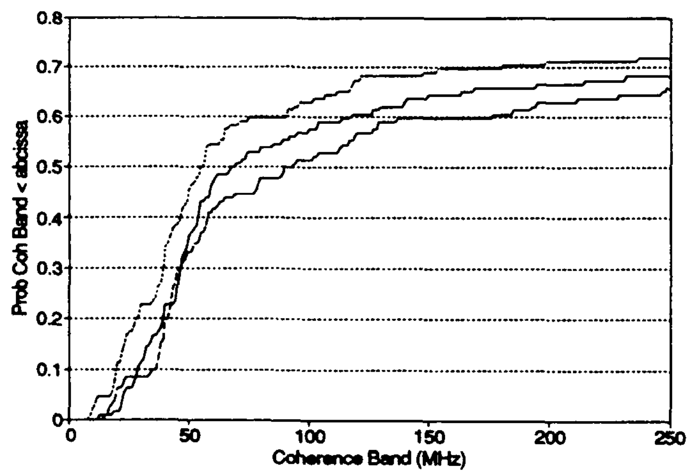
Table VI: Coherence Bandwidth for 2 antenna heights and three frequencies for OBS situations.

Location	2.4 GHz				4.75 GHz				11.5 GHz			
BW	6 dB Coh BW		3dB Coh BW		6 dB Coh BW		3 dB Coh BW		6 dB Coh BW		3 dB Coh	
	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m	3m	1.5m
3G11	44	40	20	19	44	33	28	19	205	67	170	111
3G11-pers	49	54	41	26	28	43	5	19	49	80	10	10
Adj.rooms	48	13	20	2	119	15	90	5	105	18	184	2
2 roomsdist.	28	12	23	2	18	15	9	2	22.5	32	10	16
Conf.room	49	-	77	-	17	-	7	-	20	-	8	-
Hall way	57	-	55	-	67	-	69	-	42	-	55	-

The coherence bandwidth results show a large variance in most of the situations.

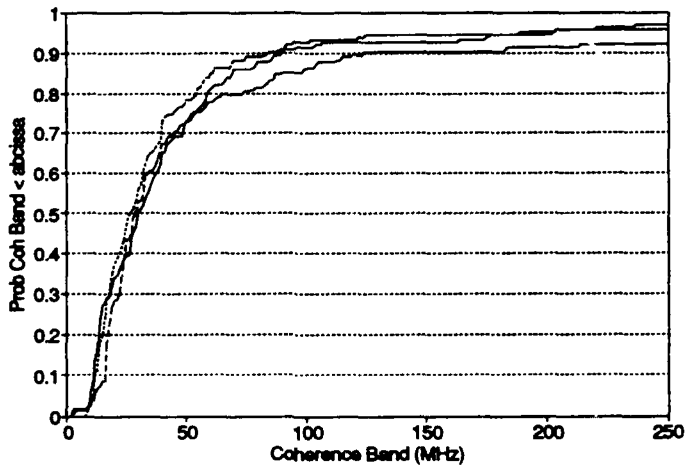
The coherence bandwidth results show a large variance in most of the situations.
In many LOS situations the correlation level did not drop blow the - 3 dB level for a bandwidth of over 250 MHz. This effect was seen for 25 to 30 percent of the measurements in the office room at all three frequencies. In the conference room this percentage was much less (5 to 7.5 percent). A remarkable observation was that at the lower frequencies 40 to 45 percent of the clusters had at least one position where the coherence bandwidth was > 250 MHz. At 11.5 GHz this percentage was even 65 percent.
With the calculated values of the coherence bandwidth B_c, the relation between τ_{RMS}, which is given in the literature and (2.12), was not found. The calculated value for α varies between 2 and 15.

The cumulative distribution functions of coherence bandwidth have been calculated with all the results separated in Line of Sight and Obstructed situations. Figure 5.22 and 5.23 shows the cumulative distribution functions.



____ 2.4 GHz .... 4.75 GHz _ _ _ _ 11.5 GHz

Fig 5.22: Cumulative distribution function of coherence bandwidth for LOS situations at 2.4 GHz, 4.75 GHz and 11.5 GHz.



____ 2.4 GHz .... 4.75 GHz _ _ _ _ 11.5 GHz

Fig. 5.23: Cumulative distribution function of coherence bandwidth for OBS situations at 2.4 GHz, 4.75 GHz and 11.5 GHz.

For LOS situations more than 27 percent of the positions have a coherence bandwidth of over 250 MHz. For OBS situations this percentage is much less (5%).

Conclusions

It is doubtfull whether the coherence bandwidth is a meaningful characteristic of a multipath radio channel, and whether it is useful in wireless system design. A clear relation between τ_{RMS} and the coherence bandwidth B_c, was not found.

6 OUTDOOR MEASUREMENTS IN FOREST ENVIRONMENT

In the military environment of the future, short range high capacity SHF and EHF data links are foreseen. Coherent wideband multipath measurements in an outdoor forest environment have been conducted, in order to investigate the typical signal propagation effects in this type of environment (mainly caused by tree trunks) at 2.4, 4.75 and 11.5 GHz.
The measurements have been carried out at two location at Ypenburg Airbase.

6.1 Measurement setup

The measurement setup for the outdoor measurements is different from the setup used for the indoor case.
For the indoor measurements all connections were made with cable, and the RF-source and Network Analyser could be placed close together. For larger distances cable losses are high which makes it difficult to get enough power at the reference input of the Network Analyser when the RF-source is placed close to the tranmit antenna or vice versa.
The costs of amplifiers and cables are very high. Furthermore, for large distances cable losses increase much faster when compared to atmospheric attenuation. Therefore, another measurement setup is preferable when the transmitter- and receiver antenna are placed at significant distances from each other. In the setup that is used here, the reference signal is transmitted from the transmitter location to the Network Analyser position by means of a highly directive link over a clear path. This system features the following advantages:

- The resulting attenuation of atmospneric propagation and antenna gain is less than the cable attenuation over that distance.
- Less expensive cables are needed to create the reference path.
- The total amplification can be limited.

The alternative measurement setup is depicted in figure 6.1.

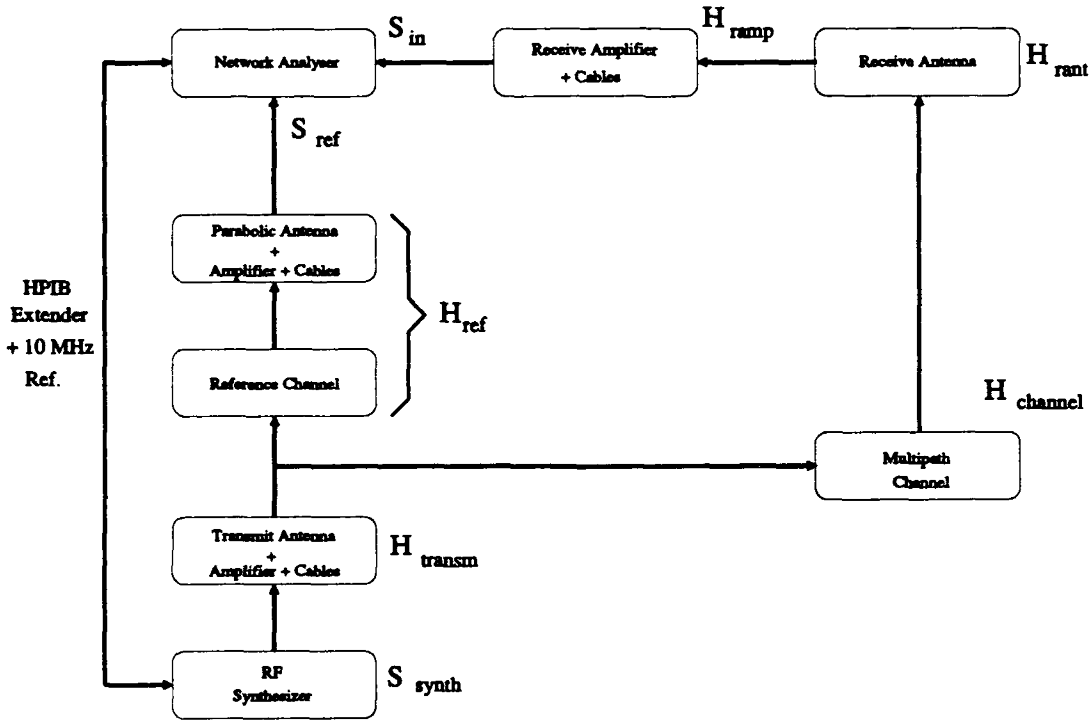


Fig. 6.1: Measurement setup for coherent wideband measurements over larger distances.

The RF-synthesizer and the Network Analyser are interconnected via an extended HPIB link and a 10 MHz reference signal.

6.2 Measurement system

The only real difference between the indoor and outdoor measurement setup is the reference signal link. Here we will analyse the influence of using the alternative reference link.

We are interested in the response of the multipath channel. The measured response is given by:

$$H_{Meas} = \frac{S_{in}}{S_{ref} \cdot H_{Cal}} \tag{6.1}$$

S_{in} is the received signal, S_{ref} is the reference input signal of the Network analyser and H_{Cal} is the calibration signal.
In figure 6.2 the calibration setup is given.

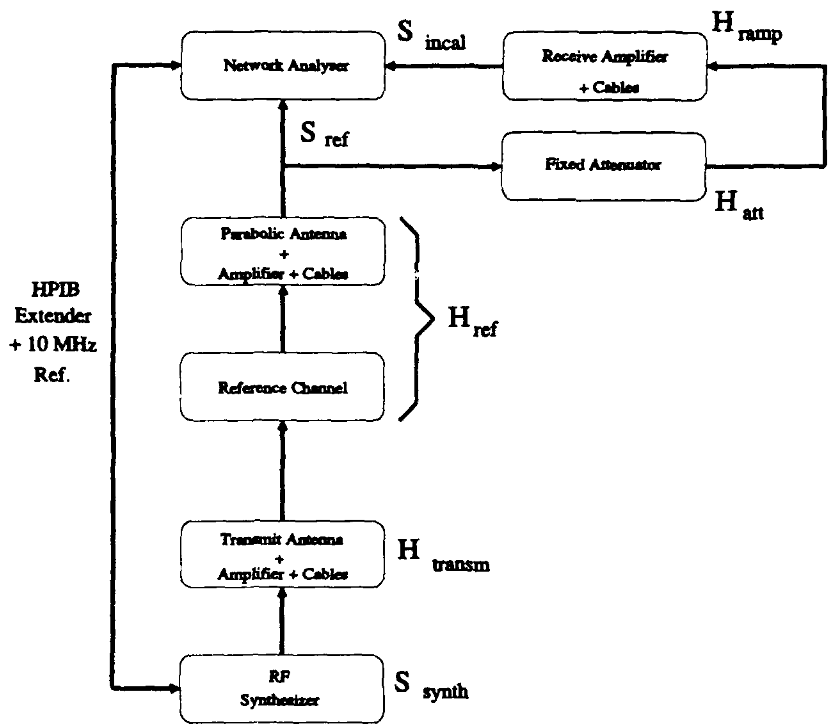


Fig 6.2: Setup for calibration.

H_{Cal} is determined by:

$$H_{Cal} = \frac{S_{incal}}{S_{ref}} \qquad (6.2)$$

with S_{incal} and S_{ref} is:

$$S_{incal} = S_{synth} H_{Transm} H_{Ref} H_{Ramp} H_{Att} \qquad (6.3)$$

$$S_{ref} = S_{synth} H_{Transm} H_{Ref} \tag{6.4}$$

So $H_{Cal} = H_{Ramp} H_{Att}$.
Now it follows for the measured response with S_{in} is:

$$S_{in} = S_{synth} H_{Transm} H_{Channel} H_{Rant} H_{Ramp} \tag{6.5}$$

that response H_{Meas} is:

$$H_{Meas} = \frac{H_{Channel} H_{Rant}}{H_{Ref} H_{Att}} \tag{6.6}$$

From this result it is clear that the measured response does not only contain the response of the multipath channel, but it is a combination of the responses of the multipath channel, the reference channel, the receive antenna response and the attenuator response. For indoor measurements H_{Meas} is the product of $H_{Channel}$, H_{Rant} and H_{Tant}. Because the antennas are wideband with nearly constant gain, H_{Rant} and H_{Tant} are assumed to be approximately 1, and so the measured response will be very close to the multipath channel response.
For the outdoor measurement setup (with the same assumptions made, and corrected for the attenuation factor H_{Att}) $H_{Meas} \approx H_{Channel}/H_{Ref}$. This means that the reference channel, which contains the influence of the physical radio path, directional antenna, amplifier and cables, may significantly influence the result when the setup is not very carefully chosen.
A parabolic dish antenna (0.9 m diameter) with a broadband logarithmic periodic feed, has been used to pick up the reference signal. This antenna can be used from 1 - 18 GHz. The relative gain variations over the measurement bands is in the order of 1 dB, which is acceptable. The amplifiers used, should have a flat response and frequency independent delay time, to make sure that the reference signal will not be distorted. The factor which is more difficult to control, is the radio path between the omnidirectional transmit antenna and the parbolic antenna. This path should be chosen in an open area without obstructions and preferably with grass covered soil to decrease the probability of reflections. Multipath reflections are significantly attenuated, because of the high directivity of the antenna (10^o at 2.4 GHz, 5^o at 4.75 GHz and 2^o at 11.5 GHz). Here it is assumed that the received signal originates only from the direct path.

With the reference link as described above it is possible to perform wideband coherent multipath measurements despite the larger distances.

6.3 Description of the measurement locations

The measurements have been performed at two locations at Ypenburg Airbase, in the winter period, so there were no leaves at the trees. The weather was good: clear sky, sunny, with temperatures just below 0^{o} C.

A schematic diagram of the measurement setup is depicted in figure (6.3).

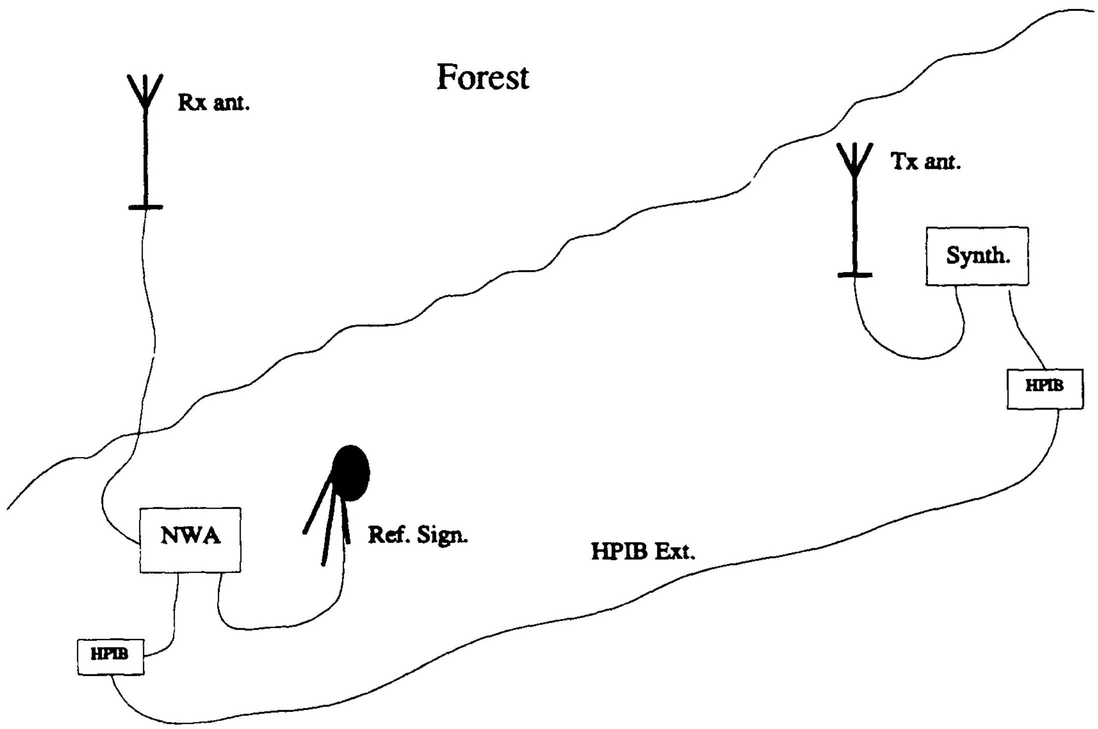


Fig 6.3: Overview of the measurement setup.

At both locations, the RF-source is placed on open grass covered terrain. The Network Analyser is placed close to the forest edge in a van, so that there is a clear unobstructed path from the transmit antenna to the parabolic antenna for reception of the reference signal.

The measurements have been carried out at 6 positions on each location. At every position a cluster of 6 measurements were conducted at 3 frequencies. The same cluster dimensions as for the indoor measurements were used (section 4.5.1). So in total 216 PDPs and frequency responses were measured.

A more detailed overview of the measurement locations is given in figure (6.4).

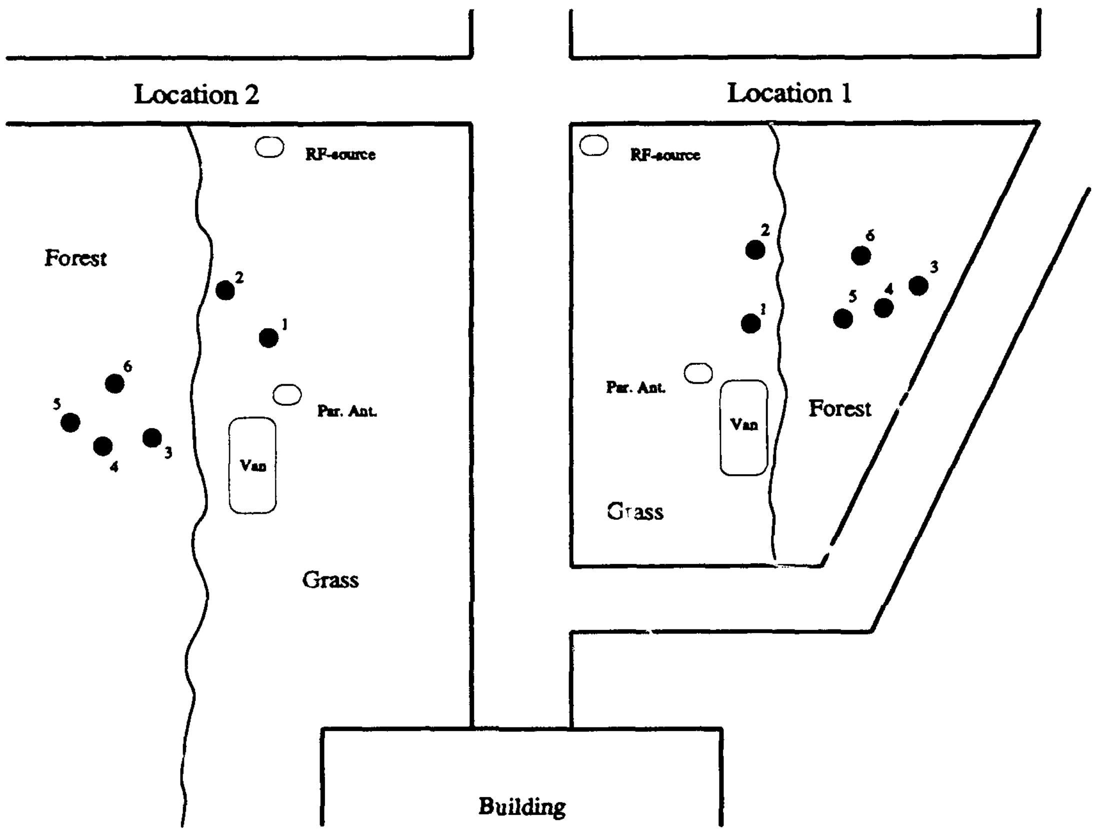


Fig 6.4: Detailed overview of the measurement locations at Ypenburg Airbase.

- Location 1

The positioning of the RF-synthesizer, parabolic antenna, the van and the measurement locations are indicated in figure 6.4. The height of the transmit and receive antennas was 2.5 m.

The distances between the RF-synthesizer and the different positions were:

- Parabolic antenna : 39 m
- Position 1 : 36 m Unobstructed
- Position 2 : 25 m Unobstructed
- Position 3 : 38 m Unobstructed
- Position 4 : 37 m Obstructed
- Position 5 : 36 m Obstructed
- Position 6 : 36 m Unobstructed

The forest consisted of quite thick trees (diameter 20 - 50 cm). The obstructed positions were chosen so that one or more tree-trunks obstructed the radio path.

- Location 2

The positioning of the RF-synthesizer, parabolic antenna, the van and the measurement locations are indicated in figure 6.4.
The distances between the RF-synthesizer and the different positions were:

-	Parabolic antenna	: 41 m	
-	Position 1	: 35 m	Unobstructed
-	Position 2	: 31 m	Unobstructed
-	Position 3	: 46 m	Partly obstructed
-	Positi[illegible]	: 45 m	Partly obstructed
-	Position 5	: 43 m	Partly obstructed
-	Position 6	: 46 m	Partly obstructed

The forest consisted of thin trees (diameter 7 - 15 cm). The positions in the forests were partly obstructed and partly unobstructed, even within a cluster. It was impossible to see in advance wether a path was obstructed or not, because a very small displacment already changes the situation, due to the many thin trees.

7 RESULTS OF THE OUTDOOR MEASUREMENTS

In this chapter the results on path-loss and delay time spread τ_{RMS} of the outdoor measurements are presented. The measurements have been performed in the period December 9 - 12 at Ypenburg Airbase.

The measurement environment is already discussed in chapter 6. In this chapter the following indications are used for the locations:

- $Fld1_{LOS}$: LOS paths over grass covered field at location 1;
- $Frst1_{LOS}$: LOS paths in the forest at location 1;
- $Frst1_{OBS}$: OBS paths in the forest at location 1;
- $Fld2_{LOS}$: LOS paths over grass covered field at location 2;
- $Frst2_{OBS}$: OBS paths in the forest at location 2.

More detailed measurement values can be found in Appendix D.

7.1 Path-loss

The path-loss results at 2.4, 4.75 and 11.5 GHz are given in Tabel VII for different types of paths. In this table the difference is given w.r.t. the path-loss for the free space situation. This value has been calculated form the measured path-loss at 1 m and the distance.

Table VII: Averaged path-loss and standard deviation (σ_L) for different outdoor situations.

Situation	2.4 GHz		4.75 GHz		11.5 GHz	
	Path-loss (dB)	σ_L (dB)	Path-loss (dB)	σ_L (dB)	Path-loss (dB)	σ_L (dB)
$Fld1_{LOS}$	0	1.1	-4	1.2	0	1.6
$Fld2_{LOS}$	-2	1.2	-4	1.7	1	2.9
$Frst1_{LOS}$	-1	1.7	-5	1.1	0	0.6
$Frst1_{OBS}$	5	1.2	4	1.3	6	1.0
$Frst2_{OBS}$	6	1.2	6	2.3	9	2.2

It is important to note that the length of the different paths are about the same for all positions in both locations 1 and 2: d_{min} = 25 m and d_{max} = 46 m. This means that the free space loss for these

paths varies only within 5 dB (20log(d_{min}) = 28 dB, 20log(d_{max}) = 33 dB). Because of the small range in distance over which measurement results are available, no value for the path-loss exponent has been calculated.

As expected, path-loss increases with frequency. The path-loss for LOS situations is in good agreement with the expected values at 2.4 and 11.5 GHz, however, at 4.5 GHz a difference of 4-5 dB is found which cannot be explained.
When we correct for this difference at 4.5 GHz, the excess attenuation for OBS situations in the forest is significant: 4 - 6 dB at 2.4 GHz, 8 - 10 dB at 4.5 GHz and 6 - 10 dB at 11.5 GHz.
When a LOS situation existed when the receiver antenna was located in the forest, path-loss was comparable with the loss in a clear LOS situation in the open field.
The standard deviation in all cases is very small (in the order of 1 dB), but increases slightly with frequency.
Forest 1, which consisted of thick trees (diameter 30 - 50 cm) but was not very dense, caused less path-loss than forest 2, which consisted of thin trees (diameter 7 - 15 cm) but was very dense.
It should be noted that the measurements were carried out in the winter period when the trees were leafless and there was no undergrowth with leaves. It is expected that the results presented here will change significantly when they are repeated in the spring or summer season.

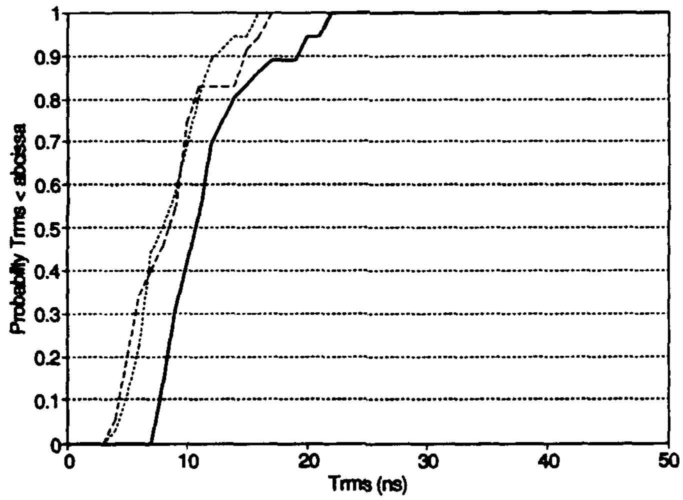
7.2 RMS delay time spread

The results for the RMS delay time spread τ_{RMS}, at 2.4, 4.75 and 11.5 GHz, are given in Tabel VIII for different types of paths.

Table VIII: Average delay time spread τ_{RMS} and standard deviation (σ_τ) for different outdoor situations.

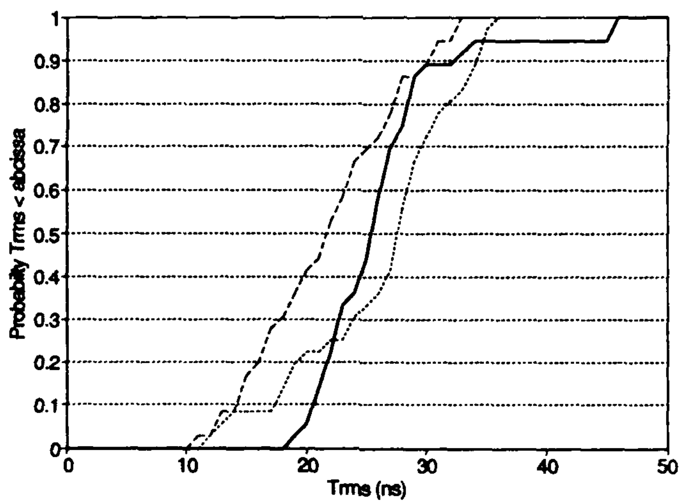
Situation	2.4 GHz		4.75 GHz		11.5 GHz	
	τ_{RMS} (ns)	σ_τ (dB)	τ_{RMS} (ns)	σ_τ (dB)	τ_{RMS} (ns)	σ_τ (dB)
$Fld1_{LOS}$	8.6	1.0	10.5	2.1	9.2	0.7
$Fld2_{LOS}$	11.2	1.0	8.4	3.9	11.4	4.4
$Frst1_{LOS}$	14.9	4.8	6.5	1.0	5.1	1.0
$Frst1_{OBS}$	28.7	9.2	26.9	5.3	21.4	4.4
$Frst2_{OBS}$	24.6	2.7	25.7	7.0	21.6	6.8

In figures 7.1 and 7.2 the cumulative distribution of τ_{RMS} is given for LOS path and OBS paths respectively, at 2.4, 4.75 and 11.5 GHz.



____ 2.4 GHz .... 4.75 GHz _ _ _ _ 11.5 GHz

Fig. 7.1: Cumulative distribution function of delay time spread for LOS situations at 2.4 GHz, 4.75 GHz and 11.5 GHz.



____ 2.4 GHz .... 4.75 GHz _ _ _ _ 11.5 GHz

Fig. 7.2: Cumulative distribution function of delay time spread for OBS situations at 2.4 GHz, 4.75 GHz and 11.5 GHz.

For all LOS situations τ_{RMS} is quite small: ≈10 ns, and about the same at 2.4 GHz, 4.75 GHz and 11.5 GHz. It shows that outside the forest but close to the forest edge, already multipath is present, which is of about the same level as for LOS paths in the forest.

The LOS paths in forest 1 showed a strange effect: τ_{RMS} is quite large at 2.4 GHz (when compared to the other LOS cases), but decreases significantly at the other frequencies. An explanation for this effect might be that in the interaction between the e.m. waves and the trees, the diffraction effect dominates at the lower frequency, whereas at the higher frequencies (smaller wavelengths) shadowing becomes more important.

For the OBS cases (which are all in the forest) τ_{RMS} increases to 2 - 3 times the value of the LOS cases: ≈25 ns. This value again is about the same for all frequencies (with a slight decrease for 11.5 GHz: ≈21 ns).

The variance found in τ_{RMS} is very small in the LOS cases, but increases in the OBS situations as is clearly seen when the cumulative density functions in figures 7.1 and 7.2 are compared.

With (2.10) the maximum usable bitrates, which can be applied without further measures, are:

LOS: ≈ 25 Mbit/s

OBS: ≈ 10 Mbit/s

Conclusions

In general it can be stated that LOS paths have less path-loss and lower τ_{RMS} than OBS paths.

In LOS situations the path-loss is significantly less compared to OBS situations (8 - 10 dB), also when the receiver is located in the forest. When a transmission system has to be located in the forest, the transmitter and receiver locations should be chosen so that a LOS path exists.

The same trend was found for the behaviour of τ_{RMS}. The amount of multipath for unobstructed paths in the forest is about the same as for locations just outside the forest. In LOS situations (also in the forest) τ_{RMS} was less (≈ 10 ns) than in OBS situations (≈ 25 ns). This means that in LOS situations data rates in the order of 25 Mbit/s can be applied and in OBS cases 10 Mbit/s (without the use of equalizing or diversity techniques).

The results that are presented here for an outdoor forest environment, are derived from measurements that were carried out in the winter period when the trees were leafless. It is expected that measurements carried out in other seasons will show different results.

CONCLUSIONS AND RECOMMENDATIONS

These conclusions and recommendation concern the final report of the project "Short Range Propagation Measurements at 2.4, 4.75 and 11.5 GHz in Indoor and Outdoor Environments". This project was carried out in cooperation with the Technical University of Delft.

1. At TNO Physics and Electronics Laboratory a measurement system has been developed to perform wideband coherent propagation measurements at 2.4 GHz, 4.75 GHz and 11.5 GHz. The measurement system is based on the HP 8510C network analyser and is computer controled. From the measured data relevant channel parameters for wideband communication systems design, as path-loss and delay time spread, have been calculated.

2. With this measurement system propagation measurements have been carried out in indoor and outdoor environments at 2.4, 4.75 and 11.5 GHz, at distances within pico-cellular dimensions (< 50 m), in order to compare the results.
For the outdoor measurements (distance > 30 m) a special technique using a directive link was applied, to transfer the reference signal to the network analyser measurement system. This technique makes it possible to extend the range to distances > 30 m, which could not be overcome previously due to high cable losses.
In total over 1000 measurements have been performed under different conditions.

3. Indoor environment

The indoor environment consisted of office rooms with different dimensions. Measurements have been carried out over line-of-sight (LOS) paths and obstructed (OBS) paths within a single room and between different rooms, and with applying different antenna heights. Also the influence of people being present has been investigated.

- Path-loss

From the path-loss results the parameters of a simple path-loss model have been determined. It can be concluded that this model gives accurate results for LOS situations. The values for the path-loss law exponent found for LOS paths are within the range 1.8 - 2.0 for all frequencies. In OBS situations the path-loss law exponent increases with frequency and is 3.3, 3.8 and 4.5 at 2.4, 4.75 and 11.5 GHz respectively. For OBS situations however, the attenuation predictions of the simple model are not very accurate.

It is recommended to further investigate a new model which assumes discontinuous attenuation jumps at the distance of an obstacle. This model is proposed in the literature, but has not been validated yet.

- Delay time spread τ_{RMS}

The delay time spread τ_{RMS} has been determined for different types of rooms with different dimensions. It was found that τ_{RMS} increases for large rooms. In the hall way very strong fluctiations in τ_{RMS} were found. At 11.5 GHz τ_{RMS} in most cases is significantly smaller, about 30%, than τ_{RMS} at 2.4 GHz and 4.75 GHz, which are in general of about the same value.
Obstructed paths show increased τ_{RMS} values when compared to LOS paths.
In different indoor situations, the median values of τ_{RMS} at 2.4 and 4.75 GHz range from 10 - 20 ns (this implies a maximum bitrate of 12 - 25 Mbit/s). The median values for τ_{RMS} at 11.5 GHz ranges from 5 - 15 ns (this implies a maximum bitrate of 16 - 50 Mbit/s).

- Influence of people

The effects of people on path-loss, when compared to the results for an empty room, is marginal. For LOS situations the effect is negligible. When people obstruct the direct path (OBS), 4 - 5.5 dB extra attenuation was found on the average. No clear difference in behaviour was found for the three frequencies 2.4, 4.75 and 11.5 GHz. No influence of people on τ_{RMS} was found.
Because of the small number of measurements, the interpretation of these results should be handled with care.

- Coherence bandwidth

It is doubtfull whether the coherence bandwidth is a meaningful characteristic of a multipath radio channel and whether it is a useful parameter in wireless LAN system design. A clear relation between τ_{RMS} and the coherence bandwidth B_c, was not found.

4. Outdoor environment

In outdoor situations measurements have been performed over open grass covered terrain close to forest, LOS paths in forest and OBS paths in forest. Two types of forest were used for the meausrements: one with thick trees and low tree-density, and one with thin trees and high tree-density. The measurements were performed in the winter season when the trees were leafless.

- Path-loss

In LOS situations, also when the receiver is located in the forest, the path-loss is significantly less (8 - 10 dB) compared to OBS situations. When a transmission system has to be located in the forest, the transmitter and receiver locations should be chosen so that the LOS path exists.

- Delay time spread τ_{RMS}

The same trend was found for the behaviour of τ_{RMS}. The amount of multipath for unobstructed paths in the forest is about the same as for locations just outside the forest. In LOS situations (also in the forest) τ_{RMS} was less ($\approx$ 10 ns) than in OBS situations ($\approx$ 25 ns). This means that in LOS situations data rates in the order of 25 Mbit/s can be applied and in OBS cases 10 Mbit/s. This data rate can be increased by applying equalizing or diversity techniques.

It might be expected that measurements carried out in other seasons will show different results. Therefore, if the outdoor forest environment becomes of real interest for practical application, it is recommended to perform a new, more thorough, series of measurements spread out over different seasons, to incorporate the effects of leaves and different weather conditions. No measurement results are available on these effects in the literature.

5. Further work recommmended in this field

- The first Wireless Local Area Network systems and Personal Cordless Telephones are offered on the market at this moment, and are developing towards mature systems. Chances for FEL in this field are on the application level: system and network design, development of new services and application of these systems in a custom specific way. To create a market in this field for FEL, selected potential customers have to be enlighted with the possibilities of these systems, and made aware of the advantages w.r.t. their specific needs.

However, the first step for FEL should be to become familiar with the possibilities and shortcomings of practical available systems. A way to achieve this is by building a demonstrator combined with the implementation of selected services which have a high priority for possible clients.

- The knowledge on propagation effects as given in this report can be used to make reasonable estimates with respect to signal strength, interference levels and maximum bitrate. It may be

necessary to improve this knowledge w.r.t specific building types (taking into account the specific building materials and constructions used).

- The measurement results available now, form a rich practical basis for further theoretical research at TU-Delft, especially in the fields of development and verification of channel models, choice of the optimum modulation techniques, bitrate calculations and frequency diversity and equalizing techniques. These results can also be used for more practically oriented work like in system development, development of a channel simulator and testing of systems in different environments.

ABBREVIATIONS

BW	Bandwidth
CLAN	Cordless Local Area Network
CSMA	Carrier Sense Multiple Access
dB	Decibel
dBm	Decibel w.r.t. 1 mW
e.m.	Electromagnetic
DS-SS	Direct Sequence Spread Spectrum
EHF	Extremely High Frequency (30 - 300 GHz)
EIRP	Effective Isotropically Radiated Power
FAF	Floor Attenuation Factor
FFT	Fast Fourier Transform
LAN	Local Area Network
LOS	Line-Of-Sight
NWA	Network Analyser
OBS	Obstructed
PDP	Power Delay Profile
PN	Pseudo-Noise
RF	Radio Frequency
RMS	Root Mean Square
SHF	Super High Frequency (3 - 30 GHz)
SNR	Signal to Noise Ratio
UHF	Ultra High Frequency (300 - 3000 MHz)
WAF	Wall Attenuation Factor

A	Number of antenna heights
a	Path-loss law exponent
B_c	Coherence bandwidth
β	Path gain factor
C	Number of measurements in a cluster
d	Distance [m]
d_0	Reference distance
$\delta(t)$	Dirac impulse

E[ ]	Averaging operation
F	Number of frequencies
h(t)	Channel impulse response
H(f)	Channel frequency response
λ	Wave length
N	Number of paths
θ	RF signal phase
P_R	Number of positions of the receiver antenna in the room
P_{TR}	Number of positions of the transmit antenna in the room
R	Data rate
R(t)	Autocorrelation
σ	Standard deviation
τ_{RMS} / τ_{RMS}	RMS delay time spread
τ	Delay time
T_c	Chip time
ω_c	Signal frequency

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DESIGN OF THE MEASUREMENT ANTENNAS

A.1 Introduction

For the indoor propagation measurements antennas have been designed and realised for three different frequency ranges:

1. 2.15 - 2.65 GHz
2. 4.50 - 5.00 GHz
3. 11.0 - 12.0 GHz

The following requirements are made for the indoor propagation measurement antennas:

1. Constant omnidirectional radiation pattern in the horizontal plane,
2. -3 dB angle in the vertical plane as large as possible,
3. Equal antenna gains at the centre frequency of the bands of interest,
4. Small dimensions,
5. Broadband characteristics: minimum bandwidth > 0.5 GHz for the 2.4 and 4.75 GHz bands, and > 1 GHz for the 11.5 GHZ band,
6. Nearly constant VSWR < 2 : 1 (VSWR = Voltage Standing Wave Ratio).

In this annex the design of the antennas which fulfil the requirements that are made is described.

A.2 Antenna choice

The most important requirement of those mentioned above is that the antenna must possess wideband characteristics. Antennas types which have these qualities are the equi-angular antenna, the log-periodical antenna, the horn antenna and the cilindrical dipool antenna. The equi-angular and the log-periodical antenna types are not further taken into account due to the very complex mechanical construction that is needed. The cilindrical antenna, actually a $\lambda/4$ dipool antenna is not suited for the large bandwidths that are needed here (about 25%); also the impedance is very frequency dependent.
Horn antennas and especially the biconical horns posses very wideband characteristics and are easy to construct. For our aim we have chosen for the biconical horn antenna. Actually this type of antenna is a horn antenna with an omnidirectional radiation pattern in the horizontal plane.

Figure A.1 is a drawing of the biconical horn antenna. Here also the parameters that will be used in the calculations that follow, are indicated.

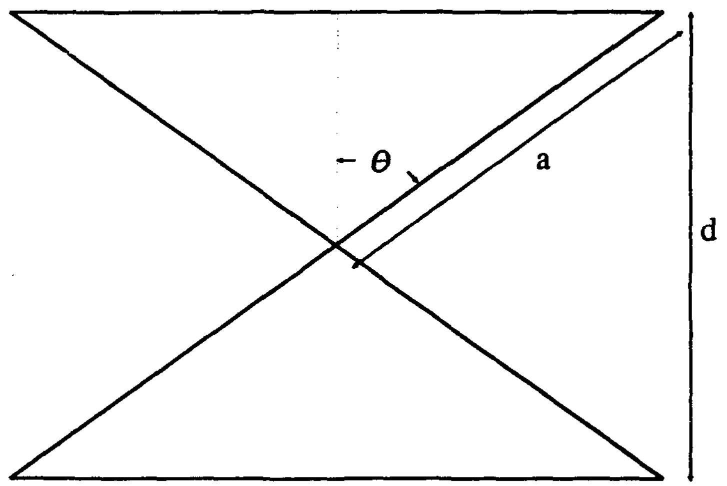


Fig. A.1: The biconical horn antenna.

The vertical radiation angle (-3 dB) and the characteristic impedance are determined by the top-angle θ and the length a of the cone rib.

A.3 Calculation of the antenna dimensions

In order to determine the dimensions of the antennas, the following parameters are needed, [A1]:

1. The top-angle θ of the antenna cone,
2. The desired impedance of the antenna, which is given by:

$$Z = 120 \log_e \cot(\theta/2) \ [\Omega] \tag{A.1}$$

The characteristic impedance of the antenna only depends on the top-angle and therefore is frequency independent.

3. The product ka, in which a is the length of the cone rib and $k = 2\pi/\lambda$, with λ the wavelength at the centre frequency of the band of interest (λ [m] = 300/freq. [MHz]).

Now the following parameters can be calculated:

1. The wavelength at the centre frequency:

2.15 - 2.65 GHz	$\lambda 1 = 0.126$ m
4.50 - 5.00 GHz	$\lambda 2 = 0.064$ m
11.0 - 12.0 GHz	$\lambda 3 = 0.026$ m

2. The k - factor:

2.15 - 2.65 GHz	k1 = 49.2
4.50 - 5.00 GHz	k2 = 98.5
11.0 - 12.0 GHz	k3 = 251.3

3. The half top-angle for $Z = 50\ \Omega$ is $\theta = 66.8^{\circ}$.

4. The influence of the product ka which determines the vertical -3 dB angle and the gain of the antenna, is shown in figure A.2.

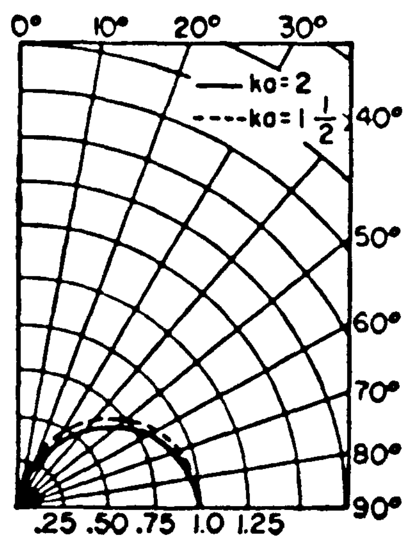


Fig. A.2: The vertical -3 dB angle dependence of ka, [A1].

For a vertical angle of 100^{0} (2.50^{0}) it follows that ka = 4.

Now the following values for the rib lengths of the different antennas can be calculated:

2.15 - 2.65 GHz	a1 = 8.12 cm
4.50 - 5.00 GHz	a2 = 4.06 cm
11.0 - 12.0 GHz	a3 = 1.59 cm

The corresponding diameters d of the cone surfaces are now with d = a sin(66.8)

2.15 - 2.65 GHz	d1 = 14.93 cm
4.50 - 5.00 GHz	d2 = 7.46 cm
11.0 - 12.0 GHz	d3 = 2.93 cm

The antenna gain can be approximated with, [A1]:

$$G_{dB} = 20.\log_{10}((2d/\lambda) - L \quad \text{(A.2)}$$

L is a gain correction factor which can be determined from figure A.3.

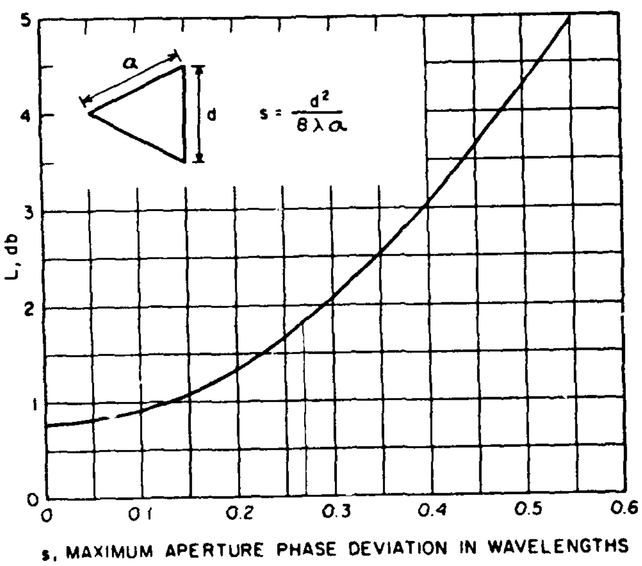


Fig. A.3: Figure of the gain correction factor L as function of $s = d^2/8\lambda a$.

For the centre frequencies of the three frequency bands it follows that:

$$s = d^2/(8\lambda a) = 0.049 \quad \text{(A.3)}$$

$$G_{dB} = 20.\log_{10}(2d/\lambda) - L = -0.8 \text{ dB} \qquad (A.4)$$

These values are equal for all three centre frequencies, because the antennas are scaled to these frequencies.

A.4 The construction of the antennas

The cones for the antennas for the two highest frequency ranges, which are quite small, have been moulded from a single block of messing. For the 2.4 GHz band, the cones are partly from messing and partly from aluminum to save weight. The coaxial connection from the antenna is made from semi-riged cable. For the two lower bands semi-riged type UT 250A, and for the highest band UT 141A has been used. The connection of the semi-riged cable with the biconical antennas for the highest frequency band gave some problems due to the expansion of the teflon insulation of the UT 141A during soldering.
For the other antennas a different techniek has been used. A messig ferrule with thread is soldered on the outer conductor of the semi-riged cable and screwed in the lower cone. The connection from the inner conductor with the upper cone is made by means of a pressure screw. This technique is outlined in figure A.4.

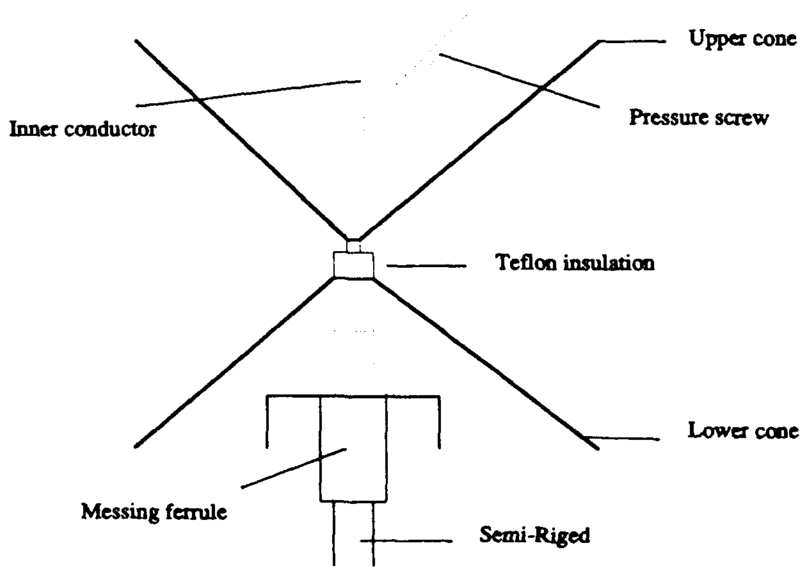


Fig. A.4: Details of the connection of the semi-riged cable to the antenna cones at 2.4 and 4.75 GHz.

A.5 Tuning of the antennas

With the help of an HP 8510B Network Analyser all the antennas have been tuned to the lowest flat VSWR over the frequency band of operation. This has been done by optimizing the distance between the two cones. The measurement results for all six antennas are shown in figure A.5 to A.7.

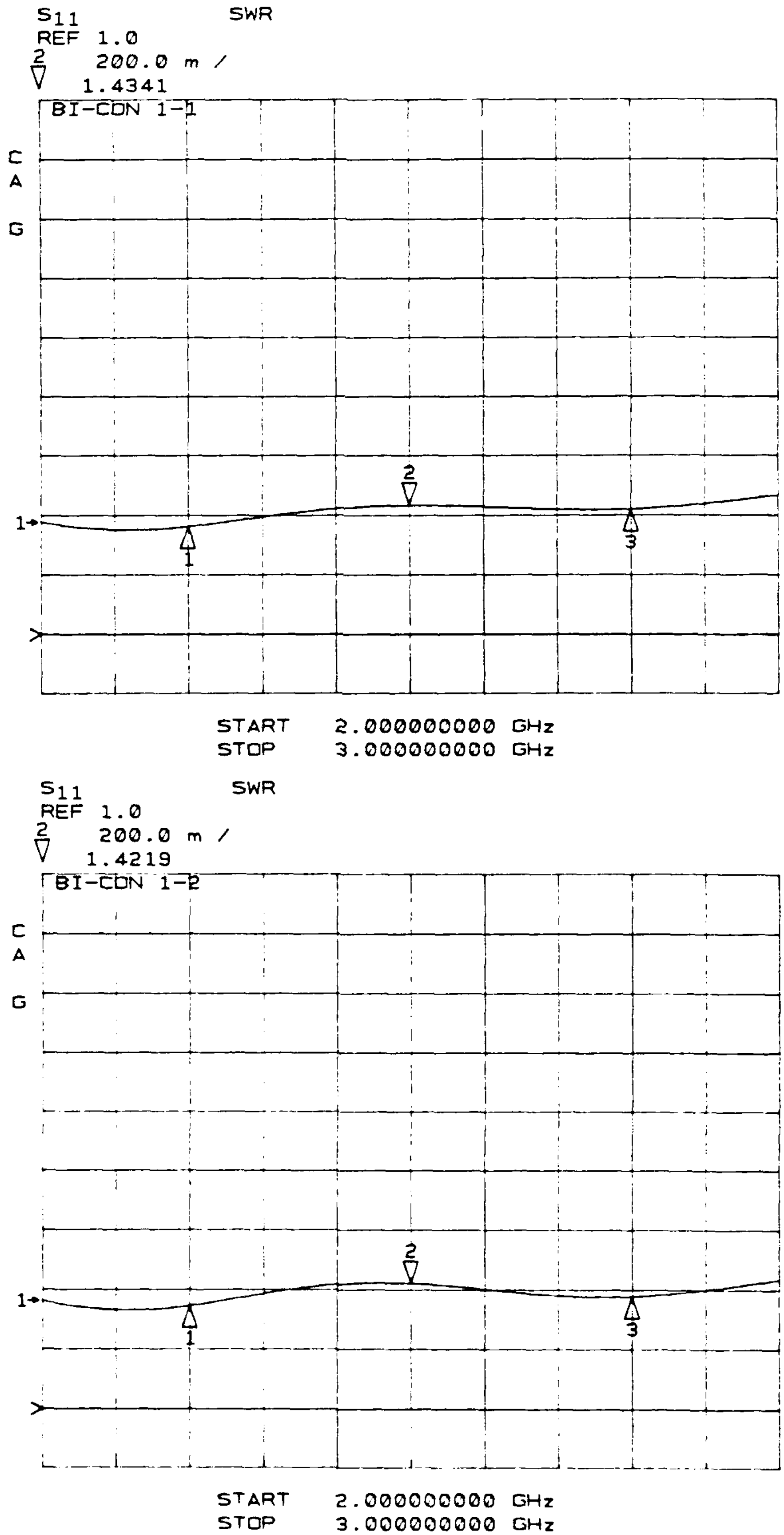
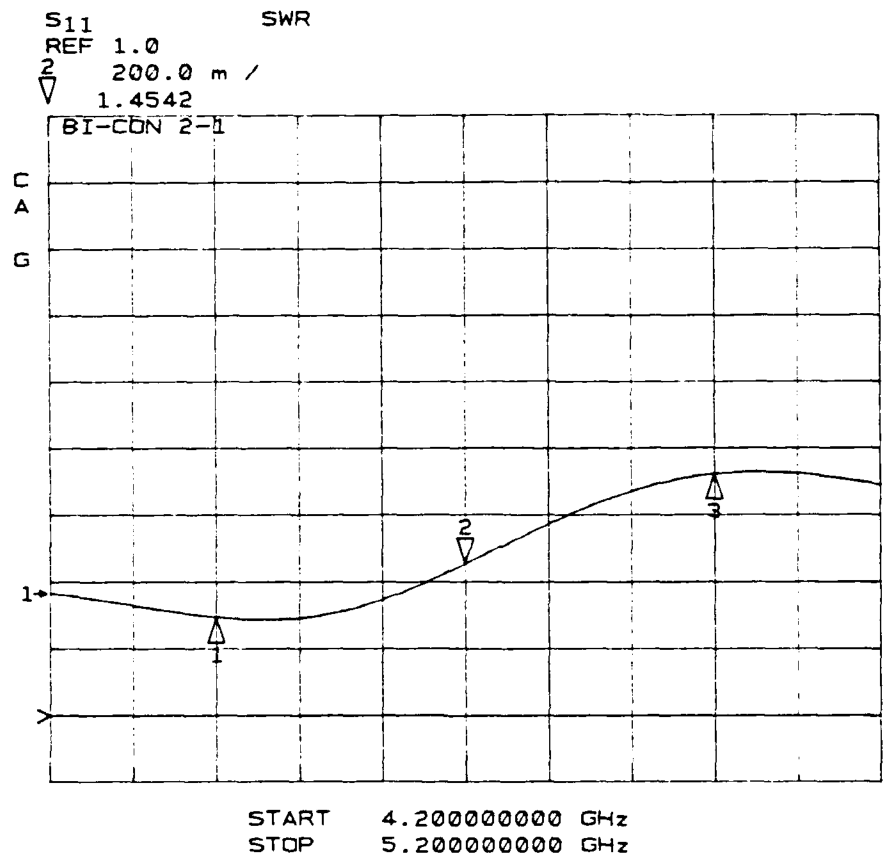


Fig. A.5: **VSWR as function of frequency for two band 1 antennas (2.15 - 2.65 GHz).**



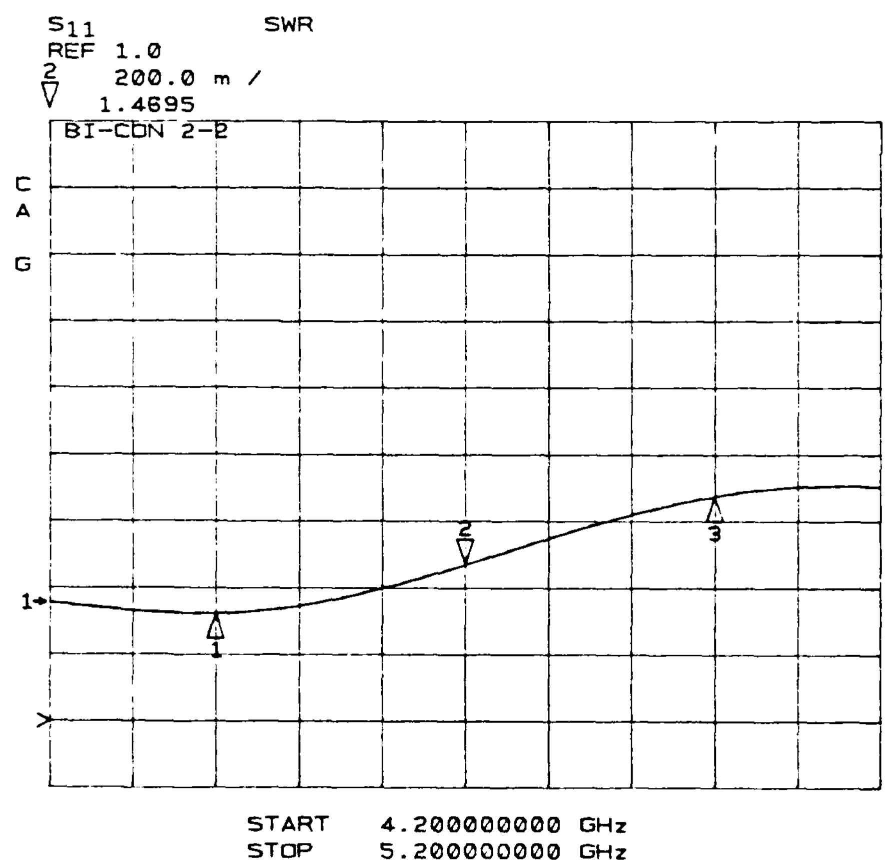
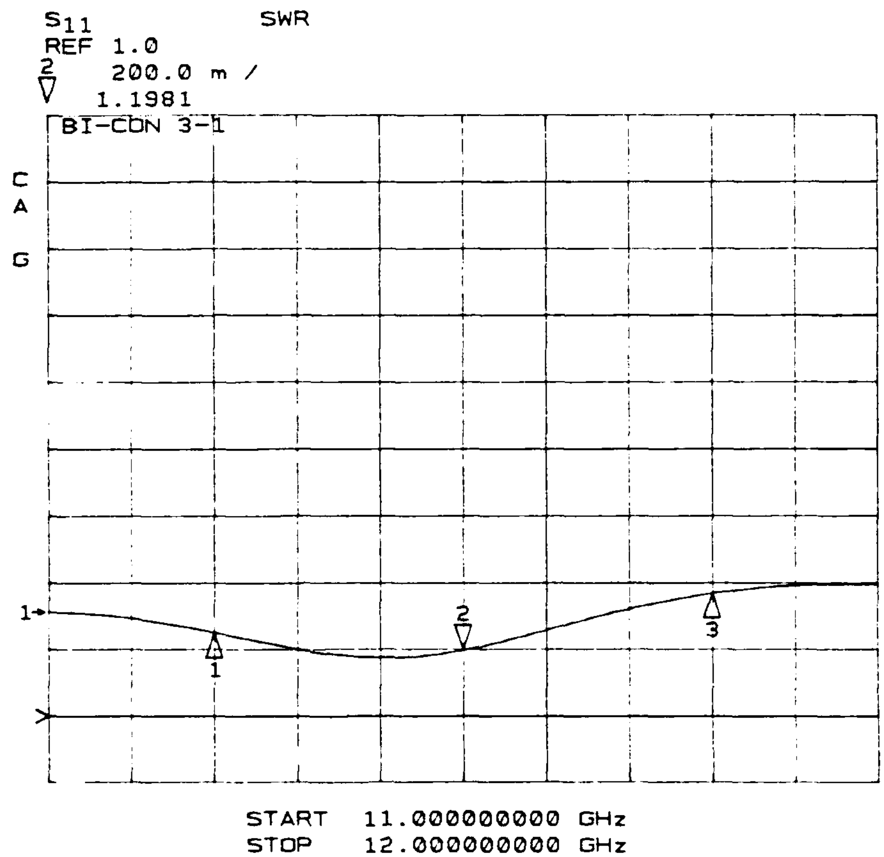


Fig. A.6: **VSWR as function of frequency for two band 2 antennas (4.50 - 5.00 GHz).**



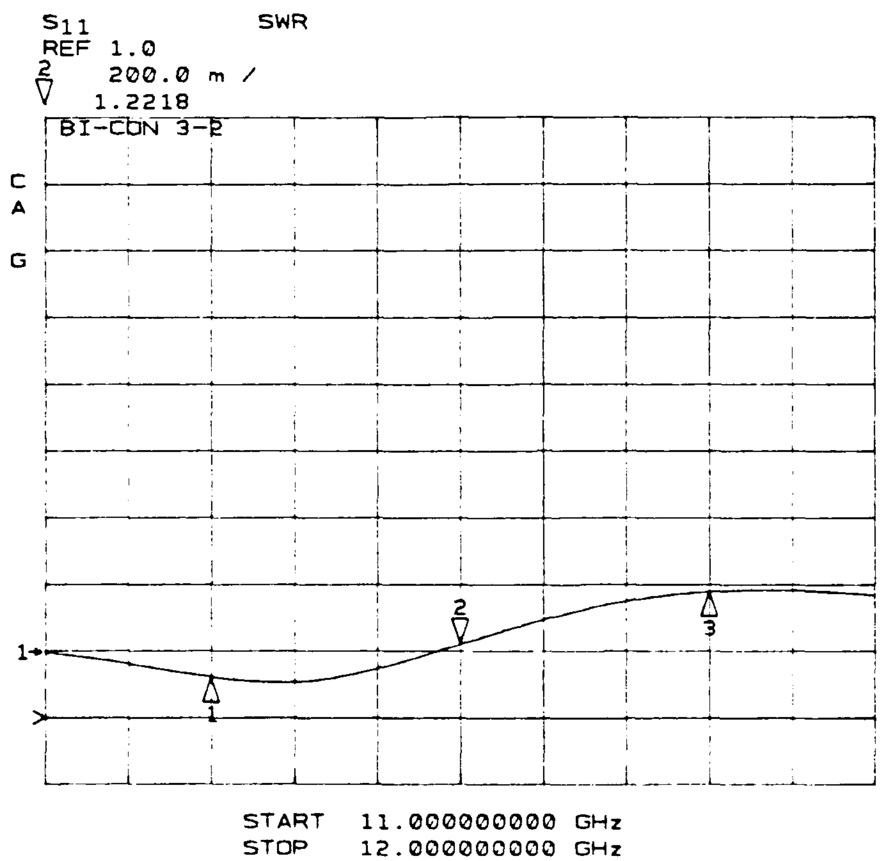


Fig. A.7: VSWR as function of frequency for two band 3 antennas (11.0 - 12.0 GHz).

A.6 Mechanical stability

In order to get a stable antenna and to relieve the inner conductor from the weight of the upper cone, it is necessary to fix the two cones w.r.t. each other. A solution to achieve this is by filling the area between the cones with foam. This has been done with one of the 11.5 GHz antennas but, although the mechanical stability was excellent, the VSWR increased to unaffordable values. It pointed out that this was caused by the fact that the foam touched the connections with the cable at the cone-tips. Removing the foam around the cone-tips gave good results, but then the filling becomes technically very difficult.
As final solution four narrow pieces of polystyrene separators have been glued between the cones with Araldite glue. For the 11.5 GHz antenna the width of the separators was chosen 4 mm and for the other antennas a width of 10 mm has been used. Also here it was necessary to remove the tips of the separators to keep the connections free and achieve good VSWR values.

[A1] H. Jasik,
"Antenna Engineering Handbook",
First edition, 1961,
McGraw-Hill Book Company Inc.

LINK BUDGET CALCULATIONS AT 2.4 GHZ, 4.75 GHZ AND 11.5 GHZ

In this appendix the link-bugets for the different frequency bands are calculated based on the losses (path-loss and cable losses) that occur and the amplification that is available.

<u>Link-budget at 2.4 GHz</u>

For the 2.4 GHZ band the following power- and pre-amplifiers are available.

Pre-amplifier Amplica ACMG 44305: 2 - 8 GHz
- Gain: 38 dB
- Noise Factor: 4 dB

Power amplifier FEL-ontwikkeling: 2.15 - 2.65 GHz
- Gain: 10 dB
- Maximum ouput power: 30 dBm

In figure B.1 the measurement set-up for 2.4 GHz is given.

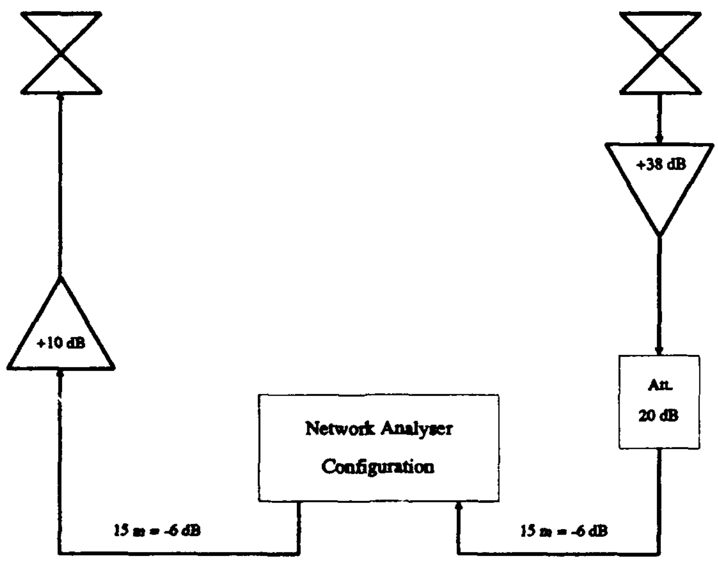


Fig. B.1: Measurement set-up for 2.4 GHz.

Link budget:

Cable length transmit branch:	15 m.	
Cable length receive branch:	15 m.	
Output Testset:	+10	dBm
Total cable loss transmit site:	6	dB
Signal power after amplification:	+14	dBm
Antenna gain:	2.5	dB
Transmitted EIRP signal power:	16.5	dBm
Minimum required input signal power:	-90	dBm
The equivalent noise level at the input of the pre-amplifier (bandwidth of the Network Analyser = 10 kHz, NF = 4 dB, P_{noise} = 4kTBF, k is the Boltzmann constant - 1.38 10^{-23} [J/K], T is the absolute temperature [K], B is the bandwidth [Hz], F is the noise figure).	-124	dBm
Antenna gain:	2.5	dB
Amplfication in the receive branch:	38	dB
Cable loss receive site:	6	dB
Extra attenuation	20	dB

The minimum required SNR (Signal-to-Noise Ratio) for good detection is 20 dB, therefore the minimum required signal power at receive antenna (including antenna gain) is -106.5 dBm. The maximum path-loss is therefore 123 dB.

In order to adjust the power level to the dynamic range of the Network Analyser, 20 dB of attenuation has been added in the receive branch after the pre-amplifier. This results in a lowest acceptable signal power at the Test-set of -92 dBm.

Link-budget at 4.75 GHz

For the 4.75 GHZ band the following power- and pre-amplifiers are available.

Pre-amplifier AMF-28-4450-20 + circulator: 4.4 - 5.0 GHz

Gain: 20 dB

Noise Figure: 2 dB

Power amplifier AMF-48-4450-29P + circulator: 4.4 - 5.0 GHz

Gain: 30 dB

Maximum output power: +29 dBm

Noise Figure: 6dB

Medium power amplifier AMF-38-4450-20P: 4.4 - 5.0 GHz

Gain: 30 dB

Maximum output power: +20 dBm

Noise Figure: 4 dB

In figure B.2 the measurement set-up for 4.75 GHz is given.

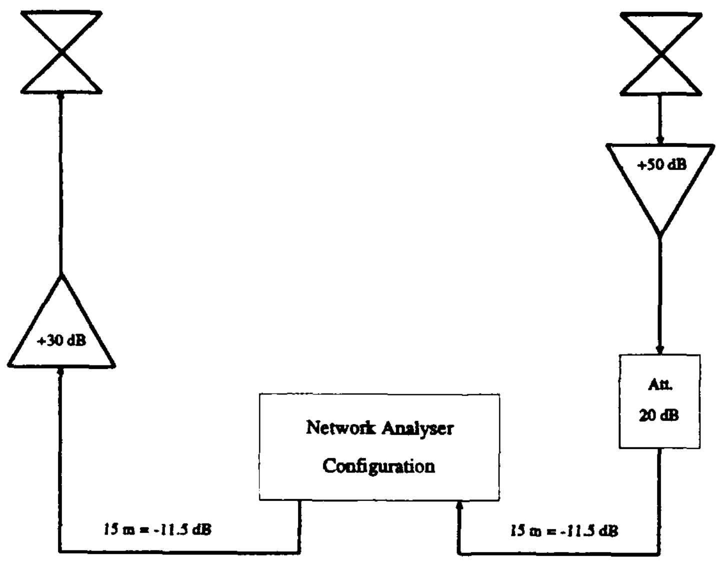


Fig. B.2: Measurement set-up for 4.75 GHz.

Link budget:

Cable length transmit branch:	15 m.	
Cable length receive branch:	15 m.	
Output Testset:	+10	dBm
Total cable loss transmit site:	11.5	dB
Signal power after amplification:	+28.5	dBm

Antenna gain:	2.5	dB
Transmitted EIRP signal power:	31	dBm
Minimum required input signal power:	-90	dBm
The equivalent noise level at the input of the first amplifier	-126	dBm
(bandwidth of the Network Analyser = 10 kHz, NF = 2 dB, P_{noise} = 4kTBF).		
Amplfication in the receive branch:	50	dB
Antenna gain:	2.5	dB
Cable loss receive site:	11.5	dB
Extra attenuation:	20	dB

The minimum required SNR (Signal-to-Noise Ratio) for good detection is 20 dB, therefore the minimum required signal power at receive antenna (including antenna gain) is -108.5 dBm. The maximum path-loss is therefore 139.5 dB.

With the 20 dB attenuation in the receive brach, addaptation to the dynamic range of the Network Analyser is achieved. This results in a lowest acceptable signal power at the Testset of -87.5 dBm.

Link-budget at 11.5 GHz

For the 11 GHZ band the following power- and pre-amplifiers are available.

2x amplifier WJ-5310-515: 8.0 - 12.0 GHz

- Gain: 33 dB
- Maximum output power: + 16 dBm
- Noise Figure: 6 dB

Amplifier WJ-5310-522: 8.0 - 12.0 GHz

- Gain: 13 dB
- Maximum output power: + 10 dBm
- Noise Figure: 6 dB

In figure B.3 the measurement set-up for 11 GHz is given.

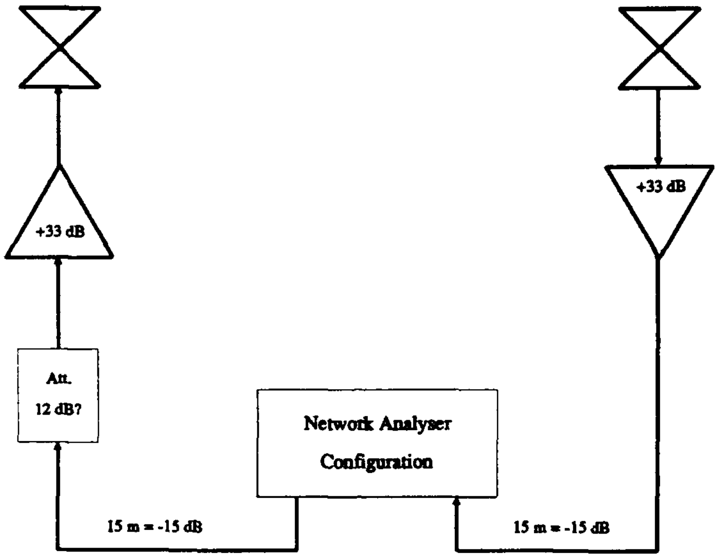


Fig. B.3: Measurement set-up for 11 GHz.

Link budget:

Cable length transmit branch:	15 m.	
Cable length receive branch:	15 m.	
Output Testset:	+10	dBm
Total cable loss transmit site:	15	dB
Signal power after amplification:	+16	dBm
Antenna gain:	2.5	dB
Transmitted EIRP signal power:	18.5	dBm
Minimum required input signal power:	-90	dBm
The equivalent noise level at the input of the first amplifier	-122	dBm
(bandwidth of the Network Analyser = 10 kHz, NF = 6 dB, P_{noise} = 4kTBF).		
Total amplfication in the receive branch:	33	dB
Antenna gain:	2.5	dB
Cable loss receive site:	15	dB

The minimum required SNR (Signal-to-Noise Ratio) for good detection is 20 dB, therefore the minimum required signal power at receive antenna (including antenna gain) is -104.5 dBm. The maximum path-loss is therefore 123 dB.
This results in a lowest acceptable signal power at the Testset of -84 dBm.

PRECAUTIONS WITH RESPECT TO RF-RADIATION EFFECTS AT 2.4 GHZ, 4.75 GHZ AND 11.5 GHZ

Electromagnetic radiation may cause some undesired effects when it interacts with the human body. The interaction is frequency and power dependent. The effects are distinguished in thermal, non-thermal and indirect effects.

- thermal effects

Heating of the body or parts of it, caused by high power density RF-radiation.

- non-thermal effect

Complaints like headache, tiredness, emotional instability etc. are called non-thermal effects of radiation. In general these effects are very difficult to identify with the presence of strong RF-fields.

- indirect effects

Indirect effects are effects like charging of unearthed objects which may cause damage when discharging via the human body.

The IRPA (International Radiation Protection Association) has defined safety rules for the permissible RF-power density to prevent from the undesired effects as mentioned above. In figure C.1 the RF-power density is indicated which is felt to be a save value.

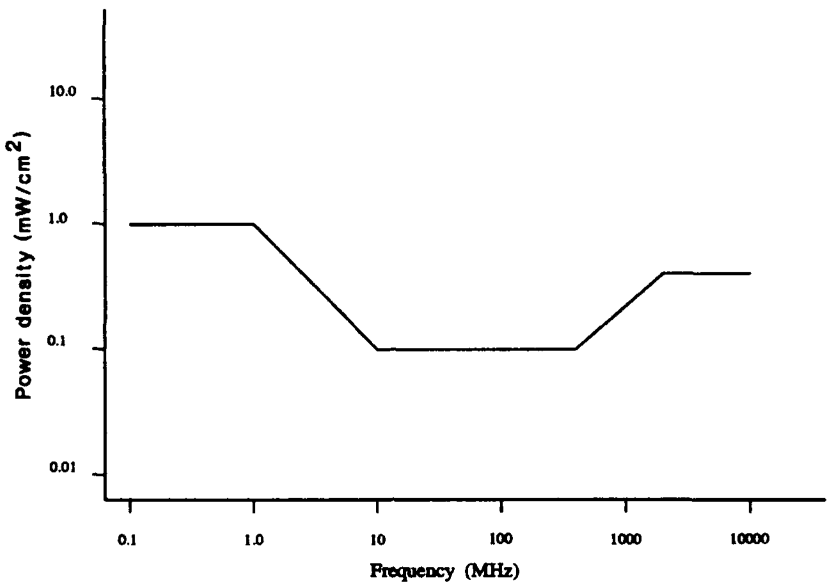


Fig. C.1: Save value for the RF-power level as function of frequency.

For the frequency range 10 - 400 MHz the value is kept lower than for the other frequency bands because in this regoin the human body may become resonant, and therefore absorb a larger fraction of the power.

For the frequency bands we are using, the save power density value is 0.5 mW/cm^2. Knowing the radiation patern of the antenna and the total radiated power, the power density can be easily calculated.

For the bi-conical antennas used, the gain is rather constant over the beamwidth $\theta = (-\alpha, \alpha)$ in the vertical plane. The area of the illuminated surface fraction of a spere with radius R is given by:

$$A_{ilum} = 4\pi R^2 \sin\alpha \qquad \text{(C.1)}$$

For the antennas used the half beamwidth angle is $\alpha = 55^o$. When the input RF-power to the antenna is +20 dBm, the safety distance is less than 5 cm. Therefore it is safe to work in the same room during the measurements. Furthermore it has to be noted that during the measurements RF-power is radiated during a few seconds, whereas the safety values are defined as being time averaged values over 6 minutes.

DETAILED RESULTS OF THE OUTDOOR MEASUREMENTS

In this appendix the results of the outdoor measurements are given in more detail at the cluster level.

D.1 Path-loss

D.1.1 2.4 GHz

Location	LOS/OBS	Pos.	Att. (dB)	Sigma (dB)	Distance (m)
Field 1	LOS	1	73	0.2	36
		2	71	0.2	25
Field 2	LOS	1	72	0.6	35
		2	70	0.3	31
Forest 1	LOS	3	73	1.0	46
		6	75	0.8	45
Forest 1	OBS	4	78	0.5	43
		5	80	0.4	46
Forest 2	OBS	3	81	1.7	37
		4	83	0.6	36
		5	83	1.0	38
		6	83	1.0	36

Averaged values for different types of paths:

Location	LOS/OBS	Att. (dB)	Sigma (dB)
Field 1	LOS	72	1.1
Field 2	LOS	71	1.2
Forest 1	LOS	74	1.7
Forest 1	OBS	79	1.2
Forest 2	OBS	82	1.2
All LOS	LOS	72	1.8
All OBS	OBS	81	1.9

D.1.2 4.75 GHz

Location	LOS/OBS	Pos.	Att. (dB)	Sigma (dB)	Distance (m)
Field 1	LOS	1	75	0.3	36
		2	73	0.2	25
Field 2	LOS	1	77	0.3	35
		2	74	1.4	31
Forest 1	LOS	3	76	0.7	46
		6	75	0.9	45
Forest 1	OBS	4	84	1.5	43
		5	83	0.8	46
Forest 2	OBS	3	89	0.7	37
		4	85	2.4	36
		5	86	1.8	38
		6	89	0.6	36

Averaged values for differe nt types of paths:

Location	LOS/OBS	Att. (dB)	Sigma (dB)
Field 1	LOS	74	1.2
Field 2	LOS	75	1.7
Forest 1	LOS	75	1.1
Forest 1	OBS	84	1.3
Forest 2	OBS	87	2.3
All LOS	LOS	86	2.5
All OBS	OBS	75	1.4

D.1.3 11.5 GHz

Location	LOS/OBS	Pos.	Att. (dB)	Sigma (dB)	Distance (m)
Field 1	LOS	1	88	0.3	36
		2	85	0.3	25
Field 2	LOS	1	88	0.3	35
		2	87	1.3	31
Forest 1	LOS	3	89	0.6	46
		6	89	0.6	45
Forest 1	OBS	4	95	0.8	43
		5	94	0.3	46
Forest 2	OBS	3	100	1.5	37
		4	101	0.3	36
		5	97	0.6	38
		6	102	1.0	36

Averaged values for different types of paths:

Location	LOS/OBS	Att. (dB)	Sigma (dB)
Field 1	LOS	87	1.6
Field 2	LOS	87	2.9
Forest 1	LOS	89	0.6
Forest 1	OBS	95	1.0
Forest 2	OBS	100	2.2
All LOS	LOS	87	2.1
All OBS	OBS	98	3.1

D.2 Delay time spread τ_{RMS}

D.2.1 2.4 GHz

Location	LOS/OBS	Pos.	Mean τ_{RMS} (ns)	Sigma (ns)	Distance (m)
Field 1	LOS	1	8.3	0.8	36
		2	9.0	1.2	25
Field 2	LOS	1	10.6	1.16	35
		2	11.7	0.3	31
Forest 1	LOS	3	13.7	3.4	46
		6	18.5	3.1	45
Forest 1	OBS	4	21.8	2.9	43
		5	35.6	8.0	46
Forest 2	OBS	3	26.4	1.3	37
		4	24.1	2.5	36
		5	26.4	2.0	38
		6	21.5	1.4	36

Averaged values for different types of paths:

Location	LOS/OBS	Mean τ_{RMS} (ns)	Sigma (ns)
Field 1	LOS	8.6	1.0
Field 2	LOS	11.2	1.0
Forest 1	LOS	14.9	4.8
Forest 1	OBS	28.7	9.2
Forest 2	OBS	24.6	2.7
All LOS	LOS	11.6	3.8
All OBS	OBS	26.0	6.0

D.2.2 4.75 GHz

Location	LOS/OBS	Pos.	Mean τ_{RMS} (ns)	Sigma (ns)	Distance (m)
Field 1	LOS	1	12.2	1.6	36
		2	8.9	1.0	25
Field 2	LOS	1	11.7	2.4	35
		2	5.1	0.9	31
Forest 1	LOS	3	9.9	0.5	46
		6	6.5	1.5	45
Forest 1	OBS	4	28.0	6.4	43
		5	25.8	4.3	46
Forest 2	OBS	3	30.1	3.7	37
		4	19.9	7.1	36
		5	22.8	7.8	38
		6	30.1	1.8	36

Averaged values for different types of paths:

Location	LOS/OBS	Mean τ_{RMS} (ns)	Sigma (ns)
Field 1	LOS	10.5	2.1
Field 2	LOS	8.4	3.9
Forest 1	LOS	6.5	1.0
Forest 1	OBS	26.9	5.3
Forest 2	OBS	25.7	7.0
All LOS	LOS	8.5	3.0
All OBS	OBS	26.1	6.4

D.2.3 11.5 GHz

Location	LOS/OBS	Pos.	Mean τ_{RMS} (ns)	Sigma (ns)	Distance (m)
Field 1	LOS	1	9.0	0.8	36
		2	9.4	0.6	25
Field 2	LOS	1	15.3	0.8	35
		2	7.5	2.1	31
Forest 1	LOS	3	10.2	0.9	46
		6	5.2	1.2	45
Forest 1	OBS	4	24.2	4.2	43
		5	18.7	2.5	46
Forest 2	OBS	3	18.1	5.7	37
		4	25.9	3.3	36
		5	19.6	5.5	38
		6	20.3	7.5	36

Averaged values for different types of paths:

Location	LOS/OBS	Mean τ_{RMS} (ns)	Sigma (ns)
Field 1	LOS	9.2	0.7
Field 2	LOS	11.4	4.4
Forest 1	LOS	5.1	1.0
Forest 1	OBS	21.4	4.4
Forest 2	OBS	21.6	6.8
All LOS	LOS	8.6	3.7
All OBS	OBS	21.5	6.0

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THIS REPORT CONCERNS THE PROJECT "SHF INDOOR/OUTDOOR PROPAGATION MEASUREMENTS", WHICH HAS BEEN CARRIED OUT IN COOPERATION WITH THE TECHNICAL UNIVERSITY OF DELFT.
WITHIN THIS PROJECT A MEASUREMENT SYSTEM HAS BEEN DEVELOPED AT FEL FOR WIDEBAND COHERENT PROPAGATION MEASUREMENTS (COMPLEX FREQUENCY RESPONSE / CHANNEL IMPULS RESPONSE). MEASUREMENTS HAVE BEEN CARRIED OUT AT 2.4, 4.75 AND 11.5 GHZ IN INDOOR (OFFICE AND CONFERENCE ROOMS) AND OUTDOOR (FOREST AND OPEN TERRAIN) ENVIRONMENTS AT DISTANCES WITHIN PICO-CELLULAR DIMENSIONS (< 50 M). FOR THE OUTDOOR MEASUREMENTS A SPECIAL TECHNIQUE HAS BEEN APPLIED TO EXTEND THE RANGE TO DISTANCES > 30 M.
IN TOTAL OVER 1000 MEASUREMENTS HAVE BEEN PERFORMED UNDER DIFFERENT CONDITIONS. IN THIS REPORT DETAILS ON THE MEASUREMENT SYSTEM THAT WAS USED, AND MEASUREMENT RESULTS ON PATH-LOSS, DELAY TIME SPREAD T_{RMS} AND THE INFLUENCE OF PEOPLE ON THE CHANNEL (INDOOR SITUATION), ARE PRESENTED.
THE MEASUREMENT RESULTS THAT ARE AVAILABLE NOW, FORM A GOOD BASIS FOR FURTHER THEORETICAL RESEARCH AND VALIDATION OF THIS WORK, AS WELL AS FOR PRACTICAL APPLICATION RESEARCH.

16. DESCRIPTORS
PROPAGATION OF RADIO WAVES
MEASUREMENT
BAND 10 SHF 3-30GC

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TIME DELAY SPREAD
INDOOR ENVIRONMENT
OUTDOOR ENVIRONMENT
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22.	Archief FEL-TNO, in bruikleen aan ir. R. Overduin
23.	Archief FEL-TNO, in bruikleen aan ir. P.J. van Vliet
24.	Archief FEL-TNO, in bruikleen aan ir. P.H. Zwaard
25.	Archief FEL-TNO, in bruikleen aan ir. M.H.A. Paquay
26.	Documentatie FEL-TNO
27.	Reserve

Indien binnen de krijgsmacht extra exemplaren van dit rapport worden gewenst door personen of instanties die niet op de verzendlijst voorkomen, dan dienen deze aangevraagd te worden bij het betreffende Hoofd Wetenschappelijk Onderzoek of, indien het een K-opdracht betreft, bij de Directeur Wetenschappelijk Onderzoek en Ontwikkeling.